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The Impact of Climate Change on Rainfall Frequency in Taiwan

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ABSTRACT

The purpose of this research is to assess climate change impacts on rainfall frequency in Taiwan. The changes in future precipitation were projected statistically from general circulation model (GCM) outputs. Based on five downscaled GCM outputs [China's FGOALS-g1.0, Japan's CGCM2.3.2, the USA's CM2.0, Canada's CGCM3(T47), and France's CM3] under the SRES A1B scenario, the frequency of the maximum consecutive dry days and maximum 1-, 2-, and 3-day rainfall during 2080 - 2099 are evaluated and compared with those in the period of 1980 - 1999. The results show that by the end of the 21st century, the risk of droughts and floods over Taiwan has a tendency to increase. The distribution of water resources in Taiwan will be more uneven, with a noticeable change in the ratio of wet and dry seasons. Due to these climate change impacts, future water conservation work will be a major challenge for governments.

Key words: Climate change, Rainfall frequency, GCM

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1. INTRODUCTION

Water nurtures life. The impact of climate change on human beings is a severe challenge. The intergovernmental Panel on Climate Change (IPCC) has indicated that increased precipitation intensity and variability due to climate change will escalate the occurrence of drought and flood in many regions by greater than 90 percent (IPCC 2007). Based on the observed climate-related trends in the period of 1901 - 2005, precipitation increased over land north of 30°N and decreased over land between 30°N and 10°S after the 1970s. By the end of the 21st century, relative to 1980 - 1999, the most likely increases are 1.7 to 4.4°C for the A1B emission scenario. This scenario indicates a future characterized by rapid economic growth, global population peaks mid-century and decline thereafter, the rapid development of new and more efficient technologies, and a balanced emphasis on energy sources. The atmospheric CO_2 concentration could reach 717 ppm by 2100 (IPCC 2001). In addition, temperature increases are projected to be higher than 3°C in East Asia. Increased rainfall intensity, particularly during the summer monsoon, could increase flood-prone areas in temperate and tropical Asia.

Taiwan is located at 22 to 25°N. Hsu and Chen (2002) applied general circulation model (GCM) outputs to analyze the past 100 years of climate change features in Taiwan. The temperature increase was 1.0 to 1.4°C/100 years, much larger than the world average (0.6°C/100 years); rainfall increased in the northern area and was reduced in the south; and the number of rain days was significantly reduced. Yu et al. (2002) generated future warming climates by utilizing local historical temperature and precipitation trends in southern Taiwan showing a decrease of available water in the dry season and an increase in the wet season. Huang et al. (2003) investigated meteorological drought conditions of Taiwan between 1970 and 2000. The results show that the scope of small-scale drought (50 consecutive days without rainfall) has expanded to the upper catchments, and large-scale drought (100 consecutive days without rainfall) may occur across the plains of western Taiwan (from Hsinchu in the north to Pingtung in the south). The areas in the north and east are less prone to meteorological drought, and the annual occurrence probability of small-scale drought is less

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than 1 percent. Li et al. (2006) noted that the impact of climate change in Taiwan would reduce river flows during the dry season (November - April the following year) and increase flows during the wet period (May - October). Climate change may yield an increased frequency of droughts and floods affecting water supply and demand, and increase water resource management difficulties. Lin et al. (2010) used 21 GCMs to assess the ensemble mean of the projected temperatures and precipitation in Taiwan from 2080 to 2099, with respect to 1980 - 1999 under the SRES A1B scenario. The average increase in temperature was found to be approximately 2.3°C, while the averaged percentage changes in precipitation were found to be approximately 7.4 percent. The projection is a decrease of rainfall along the western populated area and an increase of rainfall along the eastern, less-developed regions.

This study will examine the impact of climate change on rainfall over Taiwan. The statistical items (annual rainfall, rainfall exceedance probability over time, maximum consecutive days without rain, and maximum 1- to 3-day rainfalls) are evaluated from the past (1980 - 1999) and for the future (2080 - 2099).

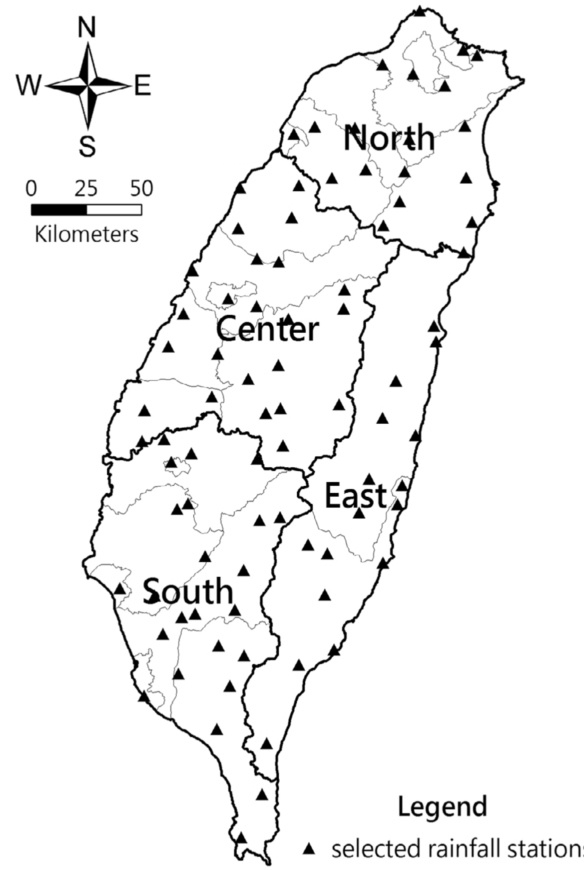

Fig. 1. Distribution and locations of four water resources regions and 83 rainfall stations.

2. DOWNSCALING AND BIAS CORRECTION

In this paper, Taiwan's four water districts (northern, central, southern, and eastern) and 83 rainfall stations are selected. The observed daily rainfall data of 1980 - 1999 from each district's rainfall stations (as shown in Fig. 1) and the IPCC's A1B scenario simulated data over 1980 - 1999 are used for validation. The five chosen GCMs are China's FGOALS-g1.0, Japan's CGCM2.3.2, the USA's CM2.0, Canada's CGCM3(T47), and France's CM3. All these models' projections over 2080 - 2099 daily rainfalls are assessed for the frequency analysis of the climate change impact on rainfall. In fact, uncertainty in climate change projections will increase with the length of the time horizon (AR4; IPCC 2007). To reduce uncertainties, an ensemble of these five climate models will be considered.

The GCM data were released by the IPCC Data Center but are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI). Because of the mismatch of spatial grid scales between the GCM outputs and realistic patterns, statistical downscaling of GCM scenario-run outputs to local climate stations was performed in three stages. The basic idea was to establish a statistical linkage between the GCM outputs and the local observations based on the data collected in 1960 - 1989 (the training period), to check the reliability of the relationship in 1990 - 2005 (the verification period), and to apply the methodology to the future projection data. For a more detailed description of the statistical downscaling of climate parameters to the Taiwan stations from the GCM scenario-run outputs, please refer to Lin et al. (2010).

This study found that the downscaled data were often biased compared with the observations. Figure 2, for example, shows that the simulated data of 1980 - 1999 by the CM2.0 climate model are larger than the observations in Taipei. This bias may lead to an underestimation or overestimation of future droughts and floods. Therefore, a conversion method, the Quadrant Transformation Method (QTM), is proposed for bias correction, where the differences between the observations and the GCM-simulated data for the present day are substantial. As shown in Fig. 3, the exceedance curve (Loucks et al. 1981) of each month for GCM's projected rainfall data from 2080 - 2099 is constructed in the 3rd quadrant. Through the relationship of the exceedance curves of the 1st quadrant (based on the observations of 1980 - 1999) and the 4th quadrant (based on GCM's simulated data of 1980 - 1999), we obtain the exceedance curve of the adjusted projections of 2080 - 2099 in the 2nd quadrant. During the correction process, the difference between the 1st and 4th quadrants is caused by GCM modeling, while the difference between the 3rd and 4th quadrants is due to climate change. The exceedance curves of each quadrant in Fig. 4 show that both curves in the 1st and 4th quadrants are inconsistent because the GCM's simulated data are generally inconsistent with the observations. However, the biases between the 1st and the 4th quadrants for the past time horizon and the 2nd with the 3rd quadrants for the future time horizon are similar. Figure 4 shows that the CM2.0 projections of 2080 - 2099 in Taipei seem overestimated, and the projected exceedance curve in the 3rd quadrant can be adjusted in the 2nd quadrant by the QTM.

3. RESULTS

3.1 Annual Rainfall

Trends of historical and projected serial data are evaluated by the Mann-Kendall test for determining whether a serial variable increases or decreases with time (Lins and Slack 1999; Yue and Wang 2004). The results indicate that there is no trend in the past and future annual rainfalls under

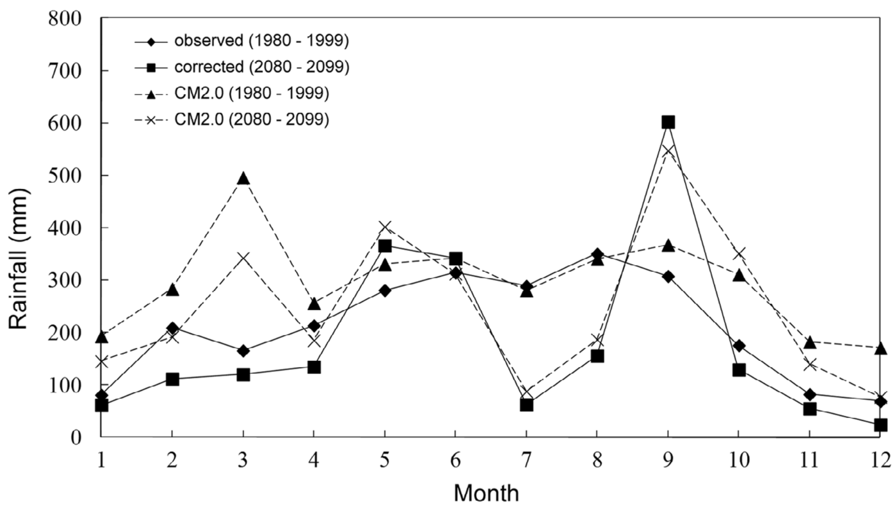

Fig. 2. Comparison of observations and adjusted CM2.0 projections in Taipei.

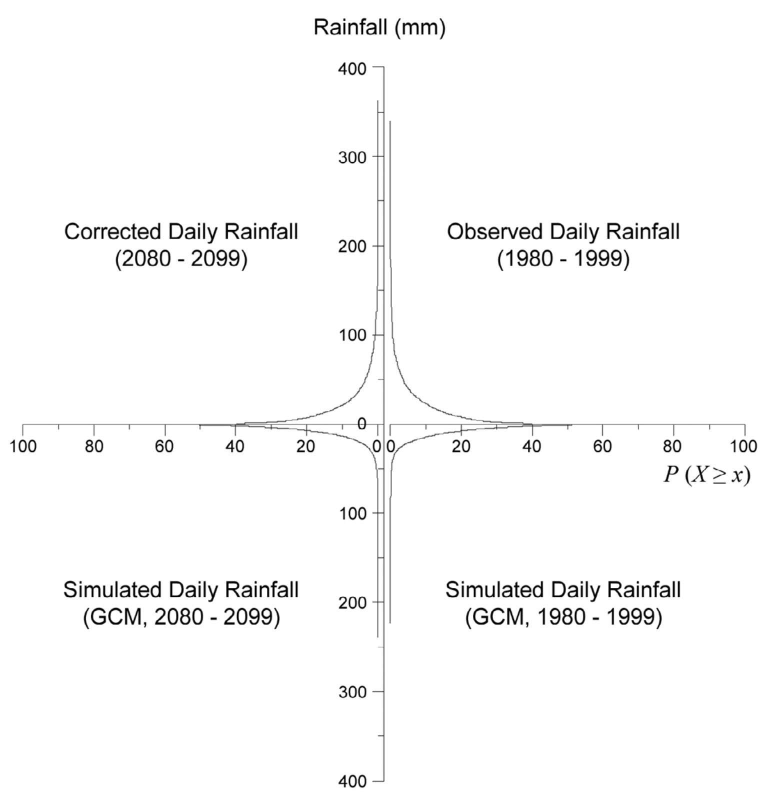

Fig. 3. Schematic diagram of quadrant conversion.

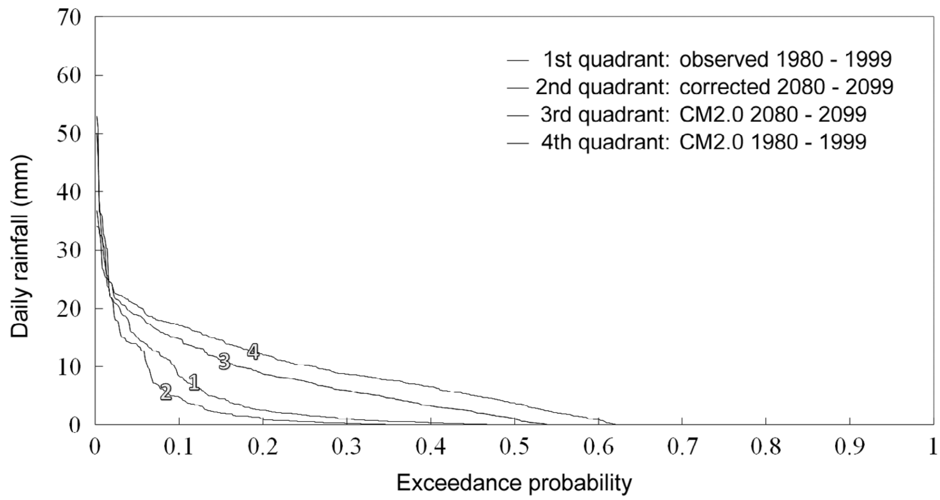

Fig. 4. Exceedance distribution of each quadrant in January of Taipei.

the 99% level of confidence. Table 1 shows the change in annual rainfall in 1980 - 1999 relative to 2080 - 2099, under the A1B scenario and based on the five GCMs. The CM2.0 projections appear to be much larger than the other GCMs, particularly in the southern region. The ensemble of GCMs indicates that by the end of the 21st century, rainfall may be slowing down in northern region, the eastern area may encounter slightly more rainfall, the rainfall variation in the central region will be small, and rainfall in south may become more severe in the future. Overall, the ratio of wet and dry rainfall seasons undergoes significant changes, especially in the eastern, central, and southern regions. More than 80 percent of the annual rainfall is concentrated during the wet season (from May to October), resulting in a serious imbalance in rainfall distribution, which will cause difficulties in water resource allocation in the future. Figure 5 gives an annual rainfall comparison of the past and future over Taiwan. The Kriging method was applied for the spatial estimation based on the best linear unbiased estimate (Huang and Yang 1998; Biau et al. 1999). The projections of most rainfall stations in the northern region are lower than the observations. For example, the annual rainfall in Taipei decreases from 2423 to 1983 mm and in Keelung from 3837 to 2984 mm. In contrast, the rainfall projections are generally much higher than the observed values in the south. The scope of the high rainfall areas is expected to expand in the future in the south and east.

3.2 Distribution of Exceedance Probability

The wet season can be divided into the plum period in May and June and the typhoon period from July through October. We can construct an exceedance probability distribution of rainfall to check the pattern in the monthly rainfall by 1980 - 1999 relative to 2080 - 2099. Figures 6a - d which represent each water district and compare the exceedance probability distribution of past and future from an optimistic 10% to a pessimistic 95%. The projected rainfalls exhibit a trend toward the wet period. The projections concentrated on the wet season are more obvious, particularly in the southern region.

3.3 Maximum Consecutive Dry Days

With higher temperatures, the climate will increase the risk of meteorological droughts, and the consecutive dry days are expected to increase in the future. In this study, the annual maximum number of consecutive dry days is designated as a random variable, and the Log-Pearson Type III is applied for frequency analysis (Haan 1977). Table 2 shows the annual maximum number of consecutive dry days associated with different return periods based on observations and the ensemble mean. Increasing frequencies were projected. The ensemble results show that the maximum consecutive dry days associated with any return period become higher in the future, no matter where the region is in Taiwan. The dry conditions in the north and south are expected to deteriorate. Compared with past records, the projected magnitude of the 50-yr drought in the north has been beyond the standard of small-scale drought (50 consecutive dry days), with more frequent deterioration from 100- to 50-yr droughts and a significant increase in drought frequency. It is also estimated that the probability of small-scale drought in the south rapidly increases from 0.2 (5-yr event) to 0.5 (2-yr event) in the future. However, the ensemble in the eastern region indicates that the maximum consecutive dry days are only slightly larger and less prone to small-scale drought in the future.

As shown in Figs. 7a - d, the contour map associated with the 2-, 10-, 50-, and 100-yr annual maximum number of consecutive dry days was established using the ordinary Kriging method, where the values at ungauged sites can be estimated. The figures show an increase in the number of consecutive dry days and have been projected across most of western Taiwan by the end of the 21st century, and large-scale drought (100 consecutive dry days) will occur along the southern coast region as the return period of 50 years is reached. In addition, a change of the future return period of droughts with an intensity of the past 100-yr events shows a 100-yr drought of the past magnitude may return more

Table 1. Comparison of rainfall by 1980 - 1999 relative to 2080 - 2099 under A1B scenario.

	Observations (1980 - 1999)		**FGOALS-g1.0 (2080 - 2099)**		**CM2.0 (2080 - 2099)**		**CGCM3(T47) (2080 - 2099)**	
	Wet season	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**
Northern	59.5% (1760 mm)	40.5% (1200 mm)	62.8% (1593 mm)	37.2% (941 mm)	70.7% (2123 mm)	29.3% (880 mm)	62.62% (1571 mm)	37.38% (938 mm)
Central	72.8% (1458 mm)	27.2% (544 mm)	82.4% (1859 mm)	17.6% (397 mm)	88.5% (2717 mm)	11.5% (353 mm)	82.32% (1624 mm)	17.68% (349 mm)
Southern	86.2% (2154 mm)	13.8% (344 mm)	92.3% (3764 mm)	7.7% (315 mm)	95.03% (5443 mm)	4.97% (284 mm)	92.29% (3240 mm)	7.71% (271 mm)
Eastern	75.1% (1749 mm)	24.9% (579 mm)	76.9% (2287 mm)	23.1% (684 mm)	83.2% (2773 mm)	16.8% (558 mm)	76.69% (1946 mm)	23.31% (591 mm)
	CM3 (2080 - 2099)		**CGCM2.3.2 (2080 - 2099)**		**Ensemble (2080 - 2099)**			
	Wet season	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**		
Northern	68.33% (1630 mm)	31.67% (755 mm)	62.61% (1633 mm)	37.39% (975 mm)	65.41% (1749 mm)	34.59% (925 mm)		
Central	88.20% (1694 mm)	11.80% (227 mm)	74.36% (1186 mm)	25.64% (409 mm)	83.30% (1842 mm)	16.70% (369 mm)		
Southern	93.86% (3805 mm)	6.14% (249 mm)	89.84% (1746 mm)	10.16% (197 mm)	92.63% (3627 mm)	7.37% (289 mm)		
Eastern	82.77% (2285 mm)	17.23% (476 mm)	70.25% (1317 mm)	29.75% (558 mm)	78.17% (2164 mm)	21.83% (604 mm)		

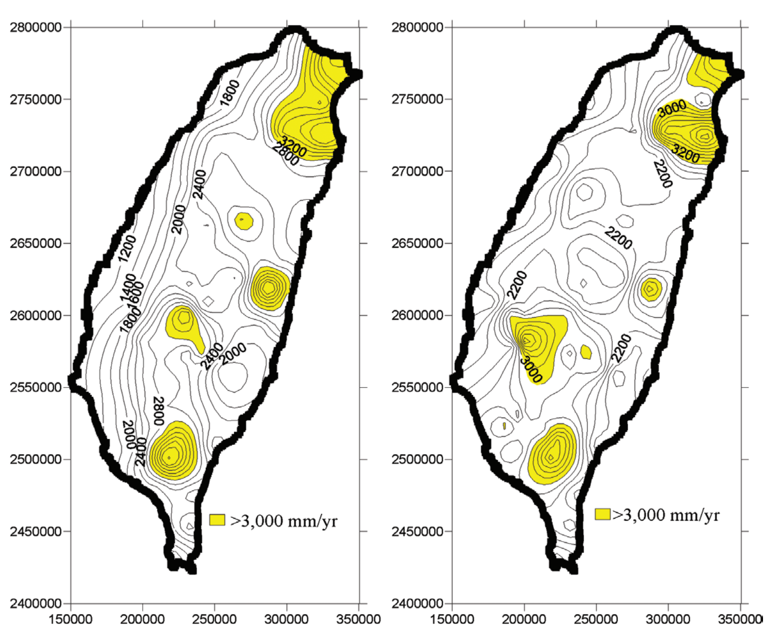

Fig. 5. Comparison of annual rainfall in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models.

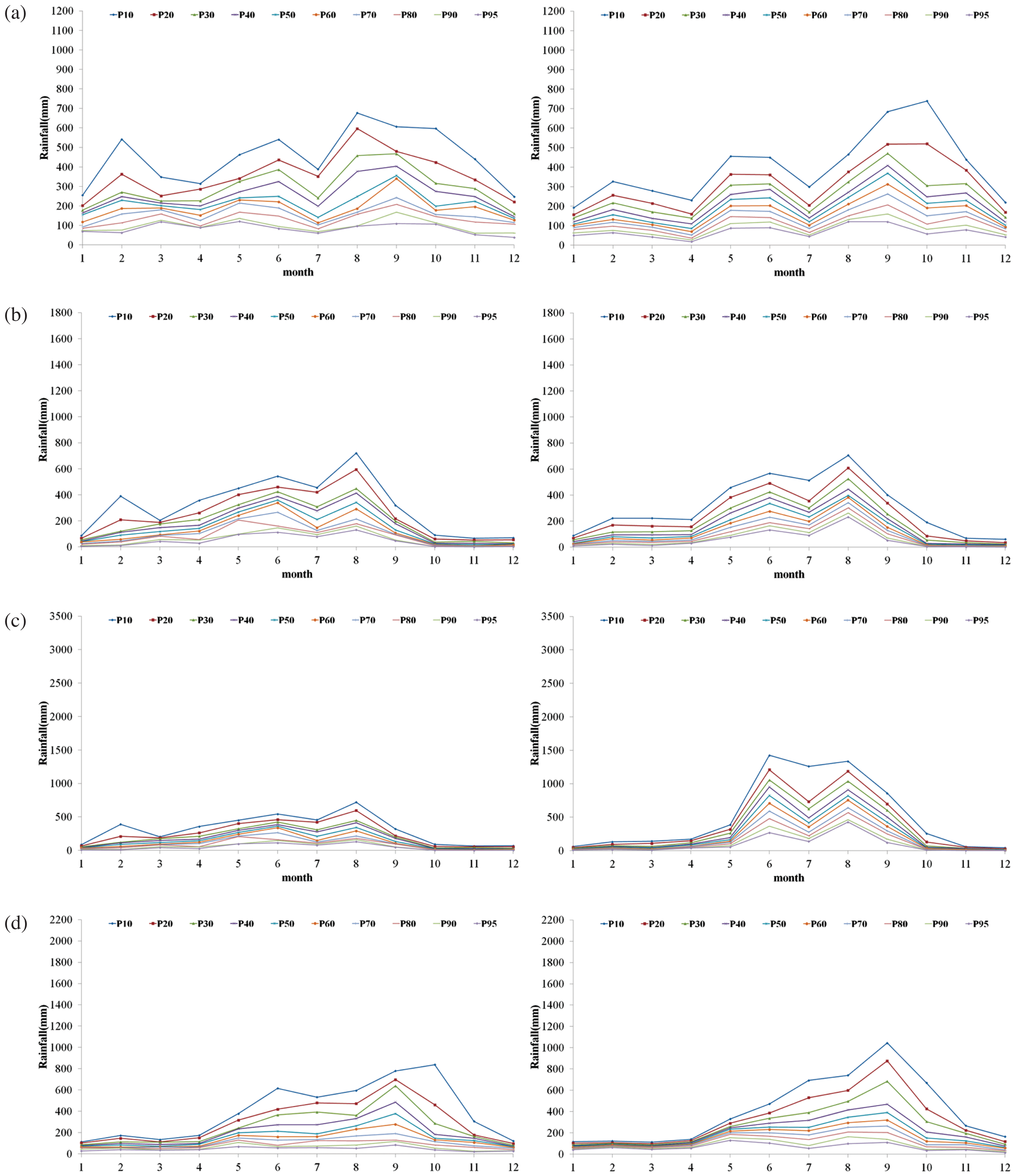

Fig. 6. (a) Comparison of exceedance curves of monthly rainfall in northern Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (b) Comparison of exceedance curves of monthly rainfall in central Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (c) Comparison of exceedance curves of monthly rainfall in southern Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (d) Comparison of exceedance curves of monthly rainfall in eastern Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models.

Table 2. Maximum consecutive dry days in Taiwan.

Return period (years)		2	5	10	25	50	100
Northern	Historical (1980 - 1999)	21	27	32	38	44	52
	Ensemble (2080 - 2099)	29	37	41	47	52	56
Central	Historical (1980 - 1999)	41	54	62	72	79	87
	Ensemble (2080 - 2099)	45	56	64	73	79	86
Southern	Historical (1980 - 1999)	42	54	62	74	83	92
	Ensemble (2080 - 2099)	49	61	69	78	85	92
Eastern	Historical (1980 - 1999)	20	26	30	35	39	44
	Ensemble (2080 - 2099)	24	30	34	39	43	46

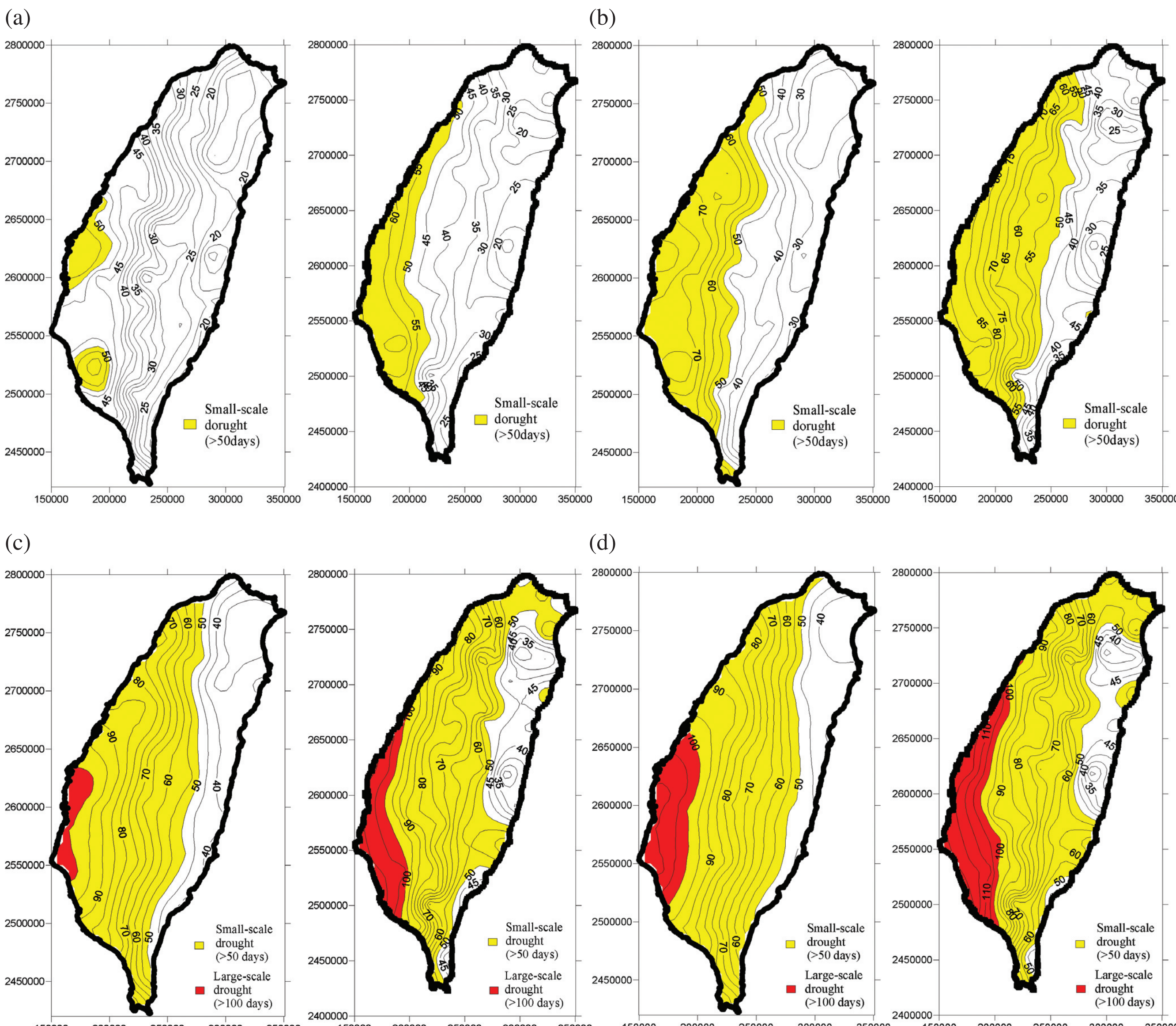

Fig. 7. (a) Comparison of 2-yr maximum consecutive dry days in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (b) Comparison of 10-yr maximum consecutive dry days in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (c) Comparison of 50-yr maximum consecutive dry days in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (d) Comparison of 100-yr maximum consecutive dry days in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models.

frequently than every 70 years in the northeastern area, as observed in Fig. 8.

3.4 Maximum 1-Day Rainfall

Due to steep slopes and heavy rainfalls, Taiwan is vulnerable to floods causing serious loss of life and property. Drainage works are dependent on the frequency analysis of rainfall data to design large and costly hydraulic structures. Annual maximum 1-day rainfall frequencies are generally requested, where extremely heavy rain, torrential rain, and extremely torrential rain, individually, indicate a daily accumulated rainfall beyond 130, 200, and 350 mm, as defined by Taiwan's Central Weather Bureau.

Table 3 demonstrates the annual maximum 1-day rainfall frequencies, based on observations and the ensemble mean. On average, the 2-yr floods in Taiwan have been beyond the standard of torrential rain. The 1-day storm seems to slow down in the northern area in the future. However, the other three areas will face a more severe flood magnitude and frequency by the end of the 21st century, particularly in the southern region, where 2-yr floods will result from extreme torrential rain, and a 10-yr flood of past magnitude may return more frequently than every 5 years. The spatial distributions relative to 2-, 10-, 50-, and 100-yr periods (see Figs. 9a - d) for the past and future also show that extremely heavy rainfall (> 130 mm day^{-1}) will occur every 2 years across the Taiwan area (Fig. 9a), and most areas are prone to extremely torrential rain (> 350 mm day^{-1}) every 10 years (Fig. 9b). Figure 10 also illustrates the change in the recurrence of 100-yr floods based on a comparison of the past (1980 - 1999) and future (2080 - 2099). The figure shows that the floods in the future will be less frequent in the north, while the other regions floods along the coastal areas will become more frequent. The adverse effects of climate on rainfall frequencies are likely to affect the flood control capacity of existing water facilities in the future, and future flood damages are expected to increase.

3.5 Maximum 2- and 3-Day Rainfalls

Typhoons occurring principally from July through October are the major sources of rainfall in Taiwan. Meanwhile, the occurrence of major typhoon-borne floods and the consequent damage is highly erratic. In fact, the rainfall record in recent years shows a great discrepancy from that of the 20th century. For example, Alishan, in southern region, observed 1624 mm/1-day, 2361 mm/2-day, and 2748 mm/3-day rainfall in August 2009 during the period of typhoon Morakot. The accumulated rainfall has exceeded a 200-yr flood in the region, which is close to a world re-

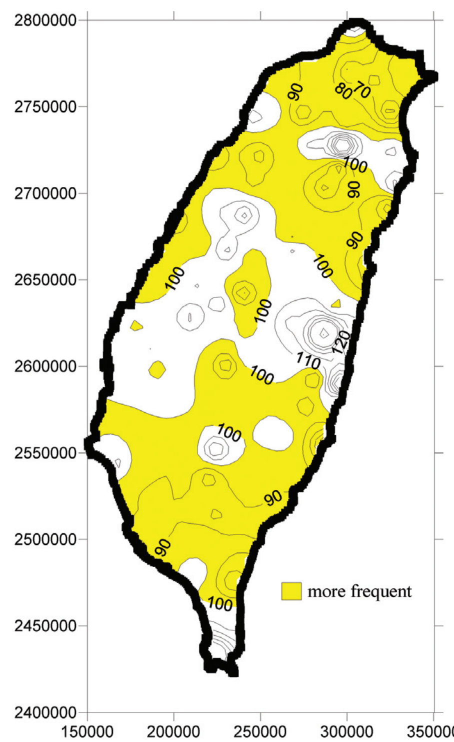

Fig. 8. Future return period of maximum consecutive dry days (2080 - 2099) with an intensity of today's 100-yr events (1980 - 1999).

Table 3. Maximum 1-day rainfall in Taiwan (mm).

Return period (years)		2	5	10	25	50	100
Northern	Historical (1980 - 1999)	220	340	419	518	593	663
	Ensemble (2080 - 2099)	207	313	392	502	595	699
Central	Historical (1980 - 1999)	181	296	386	519	631	758
	Ensemble (2080 - 2099)	232	352	435	548	641	746
Southern	Historical (1980 - 1999)	257	405	509	650	763	883
	Ensemble (2080 - 2099)	370	506	590	691	765	838
Eastern	Historical (1980 - 1999)	266	412	508	623	700	781
	Ensemble (2080 - 2099)	325	476	572	693	781	871

Fig. 9. (a) Comparison of 2-yr maximum 1-day rainfall in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (b) Comparison of 10-yr maximum 1-day rainfall in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (c) Comparison of 50-yr maximum 1-day rainfall in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models. (d) Comparison of 100-yr maximum 1-day rainfall in Taiwan between 1980 - 1999 (L) and 2080 - 2099 (R), under A1B scenario and based on an ensemble of 5 climate models.

cord. Obviously, in addition to the maximum 1-day rainfall frequency analysis, the maximum 2-day and 3-day rainfalls should be considered for their potential to alleviate some of the typhoon-related problems.

Tables 4 and 5 show the annual maximum 2- and 3-day rainfall frequencies, respectively, based on observations and the ensemble mean. Similar to the maximum 1-day rainfall frequencies, the regions most prone to a rise in the maximum 2- and 3-day flood frequencies in the future are central, southern, and eastern Taiwan. Significant changes in flood frequencies are expected in the southern region. The changes of 2- and 3-day 100-yr floods shown in Figs. 11 - 12 also demonstrate that today's 100-yr events are expected to occur more frequently in the central, southern, and eastern areas in the future.

4. CONCLUDING REMARKS

In this study, projected rainfalls under the A1B scenario were assessed in Taiwan based on five IPCC climate models. The change in rainfall by 1980 - 1999 relative to 2080 - 2099 was studied. The IPCC data were first downscaled by a regression-based statistical downscaling approach and were adjusted by the quadrant transformation method for bias correction. A comparison of past and future shows the following:

(a) Projected annual rainfall: decreasing in the northern region; increasing in the eastern, central, and southern regions; significant change in the ratio of wet and dry seasons.

(b) Exceedance probabilities over time: projections concentrated on the wet season, especially in the southern area.

(c) Droughts: increasing annual maximum consecutive dry days in the future and more prone to a rise in drought frequencies.

(d) Floods: increasing risk of maximum 1-, 2-, and 3-day rainfall in the eastern, central, and southern regions and decreasing risk in the northern region.

As a result of these changes, Taiwan's water supply, which is completely fed by rainfall, will be negatively affected in the future. Extreme droughts and floods are likely to impact human welfare. Changes in rainfall are crucial for the planning and management of future water resources. Administrations should seriously consider adaptation to changing conditions in water availability. Integrated water

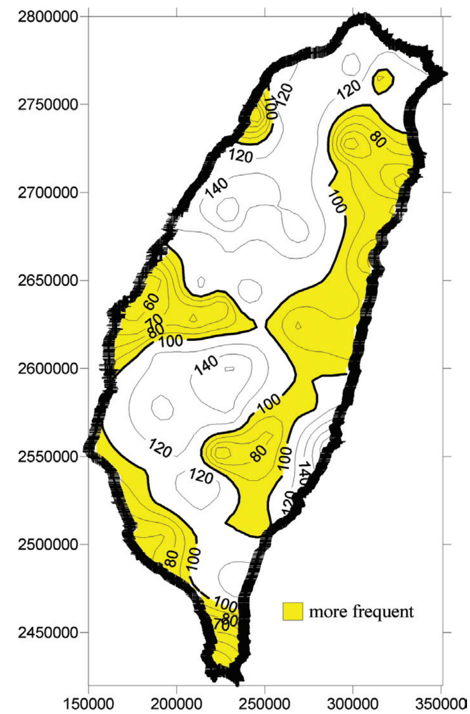

Fig. 10. Future return period of maximum 1-day rainfall (2080 - 2099) with an intensity of today's 100-yr events (1980 - 1999).

Table 4. Maximum 2-day rainfall in Taiwan (mm).

Return period (years)		2	5	10	25	50	100
Northern	Historical (1980 - 1999)	297	469	586	735	845	961
	Ensemble (2080 - 2099)	281	423	530	679	804	944
Central	Historical (1980 - 1999)	248	410	543	743	917	1116
	Ensemble (2080 - 2099)	303	483	614	797	947	1112
Southern	Historical (1980 - 1999)	371	590	745	961	1135	1322
	Ensemble (2080 - 2099)	546	769	913	1091	1224	1360
Eastern	Historical (1980 - 1999)	392	615	739	895	1033	1103
	Ensemble (2080 - 2099)	458	678	827	1021	1171	1325

Table 5. Maximum 3-day rainfall in Taiwan (mm).

Return period (years)		2	5	10	25	50	100
Northern	Historical (1980 - 1999)	337	547	690	874	1016	1187
	Ensemble (2080 - 2099)	328	501	631	815	971	1144
Central	Historical (1980 - 1999)	280	480	646	899	1126	1390
	Ensemble (2080 - 2099)	357	590	771	1036	1267	1532
Southern	Historical (1980 - 1999)	435	704	901	1167	1390	1626
	Ensemble (2080 - 2099)	659	945	1132	1367	1544	1724
Eastern	Historical (1980 - 1999)	420	694	856	1059	1198	1327
	Ensemble (2080 - 2099)	537	810	1007	1277	1499	1739

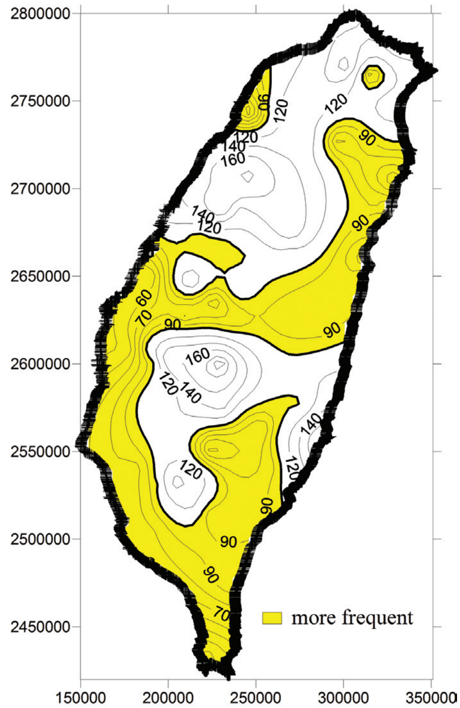

Fig. 11. Future return period of maximum 2-day rainfall (2080 - 2099) with an intensity of today's 100-yr events (1980 - 1999).

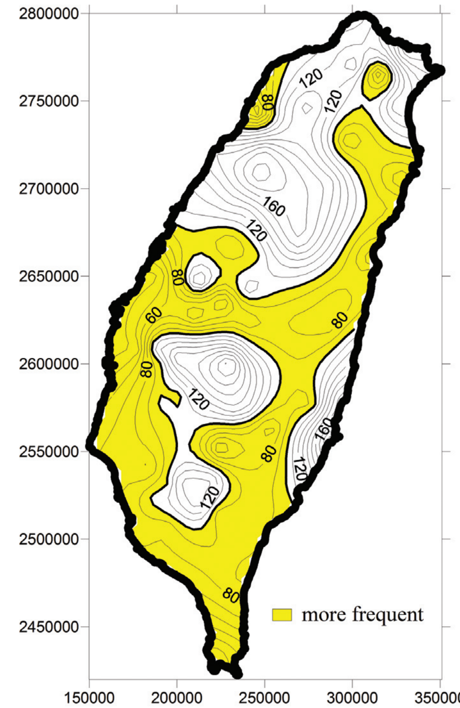

Fig. 12. Future return period of maximum 3-day rainfall (2080 - 2099) with an intensity of today's 100-yr events (1980 - 1999).

resource management on the supply side and/or demand side would be an appropriate tool for investigating adaptation measures to climate change (AR4; IPCC 2007).

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