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Change of the Probability Distribution of Annual Maximum River Discharge Derived from the d4PDF datasets at the Indochinese Peninsula

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Abstract This study investigates the differences in the probability distribution function of the future annual maximum river discharges (2051-2110) at the Indochinese Peninsula derived from the new climate datasets – database for Policy Decision making for future climate change (d4PDF). First, daily river discharge of the future period was simulated using the kinematic wave flow routing model, 1K-FRM. Based on this analysis, we combined fifteen 60-member ensembles separately for six different sea surface temperature (SST) patterns, which allows us to examine the statistical significant of the difference between the probability distribution. Then, we applied a non-parametric, two-sample Kolmogorov-Smirnov (K-S) test to the annual maximum river discharge produced by SST patterns in 15 groups. Finally, the results of each case indicate that the differences in probability distribution of the annual maximum discharges are statistically significant for the majority of the Indochinese Peninsula, except parts of the Mekong delta and southern Peninsulain Thailand. The implication of this finding should help underpin the case to merge the datasets from different SST patterns and fully utilize it in frequency analysis of extremely large datasets for a more credible hydrologic impact assessment.

Keywords *Climate change, Indochinese Peninsula, d4PDF, Kolmogorov-Smirnov test, 1K-FRM, Annual maximum daily discharge*

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Introduction

It is widely acknowledged thatwarming of climate change will have impacts on global hydrological cycle (Kundzewicz et al., 2007), with implications for the drainage basin that vary in scale from small to medium sized catchments (Chun et al., 2009; Thompson, 2012), major to regional river basins (Conway and Hulme, 1996; Arnell, 1999), and global scales (Nohara et al., 2006; Gosling et al., 2010; Nakaegawa et al., 2013; Hirabayashi et al., 2013).

To understand the effect of changing climate to those sectors, General Circulation Models (GCMs) are served as fundamental tools in future projections with continuing improvements in recent years. However, there are a range of uncertainties that are introduced throughout these hydro-meteorological impact assessments. First, uncertainty is related to the definition of the greenhouse gases emission scenarios used to force the GCMs. Secondly, uncertaintyis associated with the internal variability, which representsthe natural fluctuation of climate at daily to multi-decadal time scale (Karoly and Wu, 2005).Structural model uncertainty caused by difference use of the GCMs and leads to various projections presents a third source of uncertainty.

In general, quantification of all aspect of climate projection uncertainty ideally requires multi-model ensembles in complement with the exploration of single-model uncertainty using perturbed physics ensemble (PPEs) experiments. In practice, however, single projection of climate response to increasing GHGs emissions, are far more useful to practitioners and policymakers when they accompanied by some measure of the associated uncertainty. There have been studies that utilize the latter method, which are sets of simulation within single GCM but different choices for various parameters perturbation, with aim toanalyze uncertainty in projections of surface air temperatures, aerosol forcing, greenhousegases concentrations, and precipitation(Murphy et al., 2004; Endo et al., 2012; Mizuta et al., 2014)by using large and diverse sets of realizations to generate probability density function (PDFs) of extreme events at regional scale. Naturally, impact of climate change on surface water distribution cascades from the onset of changes in precipitation and its variability to a total runoff, and finally becomes a river discharge. Therefore, analysis of its implication to a hydrological cycle will yield significant values to the process of developing adaptation strategies.

To increase reliability of the probabilistic analysis of the future hydrological variables, one way to address this challenge is to combinemultiple projections given by PPEs. Unfortunately,relying only on large number of samples could give misleading results because the data from different perturbed ensemble might not originate from an identical source of population and could also have different prior distribution functions. For the former question, several studies were conducted and found that uncertainty in the tropical cyclone activity, precipitation, total runoff, and annual maximum daily dischargesin mainland Southeast Asia and South Asia are derived mainly from differences in the cumulus schemes rather than the different sea surface temperature (SST) patterns (Endo et al., 2012; Murakami et al., 2012; Hanittinan et al., 2015).

Here we focus on the latter part of the question; therefore, we proceed to analyze the change of the probability distribution function of annual maximum daily discharge projections, derived from the latest 60-km-mesh extremely large multi-SST ensembles of MRI-AGCM 3.2H under the same cumulus parameterization scheme (Yoshimura et al., 2011) – d4PDF, to examine the statistical difference of its prior empirical distribution function. The two-sample Kolmogorov-Smirnov test (K-S test) was conducted with the projected discharges in the Indochinese Peninsula (see Fig.1).

Characteristics of the d4PDF forcing data

The GCM outputs utilized in this study were generated by the atmospheric general circulation model MRI-AGCM 3.2H developed by the Meteorological Research Institute, Japan and archived in the d4PDF database. The dataset has two major sets of experiments: the present climate (1951-2010) with 100 perturbed ensembles and the future 4K warming experiment (2051-2110) with 90 perturb ensembles from six different SST patterns, e.g., CCSM4 (CC), GFDL-CM3 (GF), Had-GEM2-AO (HA), MIROC5 (MI), MPI-ESM-MR (MP) and MRI-CGCM3 (MR), under the Yoshimura cumulus convection scheme.

Modeling Approach: River flow routing model

River discharge in the Indochinese Peninsula region was projected using flow routing model 1K-FRM. 1K-FRM is a physically-based, distributed flow routing model with kinematic wave approximation (Hunukumbura et al., 2012). 1K-FRM was based on a watershed topography model. The topographic information used for 1K-FRM in this study was generated from processing scale-free global streamflow network datasetswith a spatial resolution of 5 arc minute.

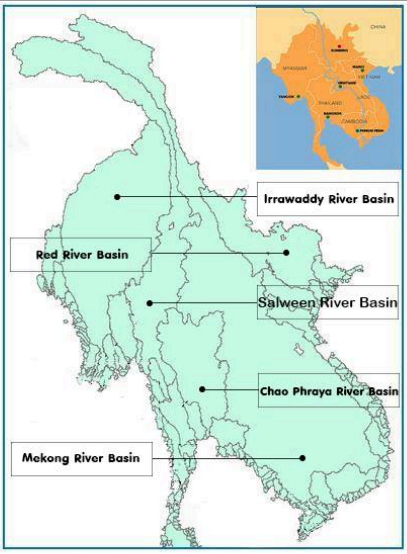


Fig. 1 The Indochinese Peninsula and its major river basins

(Masutani et al., 2006). The flow direction is defined using the 8-direction method which assumes the flow direction to the steepest downward slope to an immediate neighboring cell. The total runoff from the d4PDF is then routed by the kinematic wave equations at each flow element in accordance with the flow direction information.

Two-sample Kolmogorov-Smirnov test

The non-parametric, two-sample Kolmogorov-Smirnov test statistics (D_n) was used to determine the change in distributions of the future annual maximum daily from each possible groups of the 15-cluster 6-SST patterns 60-member (6x60x15 = 900) ensembles of the d4PDF.This measure is defined as the maximum difference between two cumulative distribution functions, ranged between 0 and 1. Therefore, in this case, the Kolmogorov-Smirnov statistics is:

$$D_{n,n'} = \sup_x \left| F_{1,n}(x) - F_{2,n'}(x) \right| \tag{1}$$

Where $F_{1,n}$ and $F_{2,n}$ are the empirical distribution functions of the first and the second sample respectively, and sup is the supremum function.

The null hypothesis H_0 for the statistical testing of prior distribution function difference of the river discharge was assumed that there is no significance difference between the annual maximum daily discharges derived from the pairs of the d4PDF SST patterns. The null hypothesis is rejected at level α if

$$D_{n,n'} > c(\alpha)\sqrt{\frac{n+n'}{nn'}} \tag{2}$$

Where n and n' are the sizes of first and second sample of the annual maximum daily discharge from two SST patterns of future climate. The value of c(α) is equal to

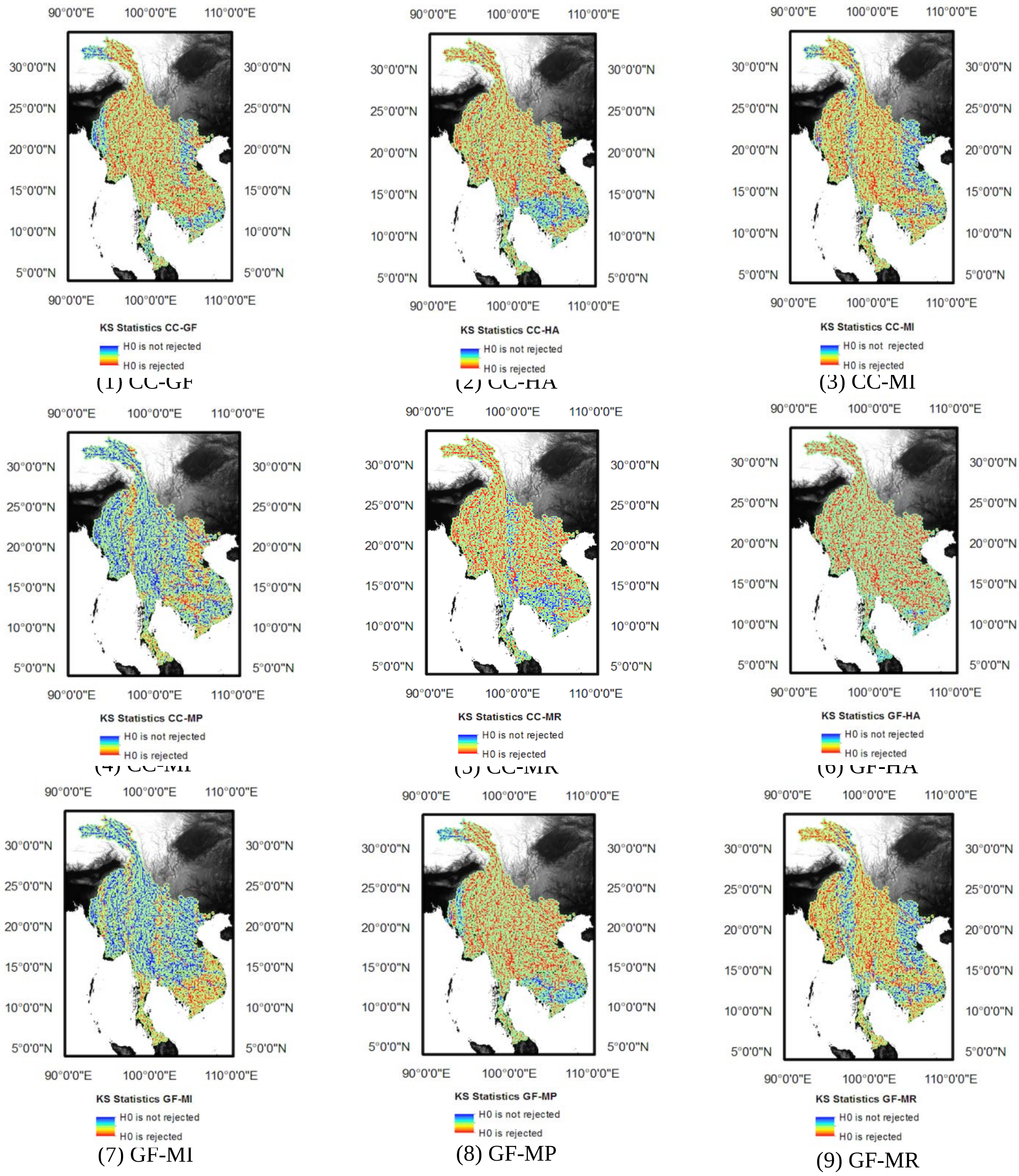


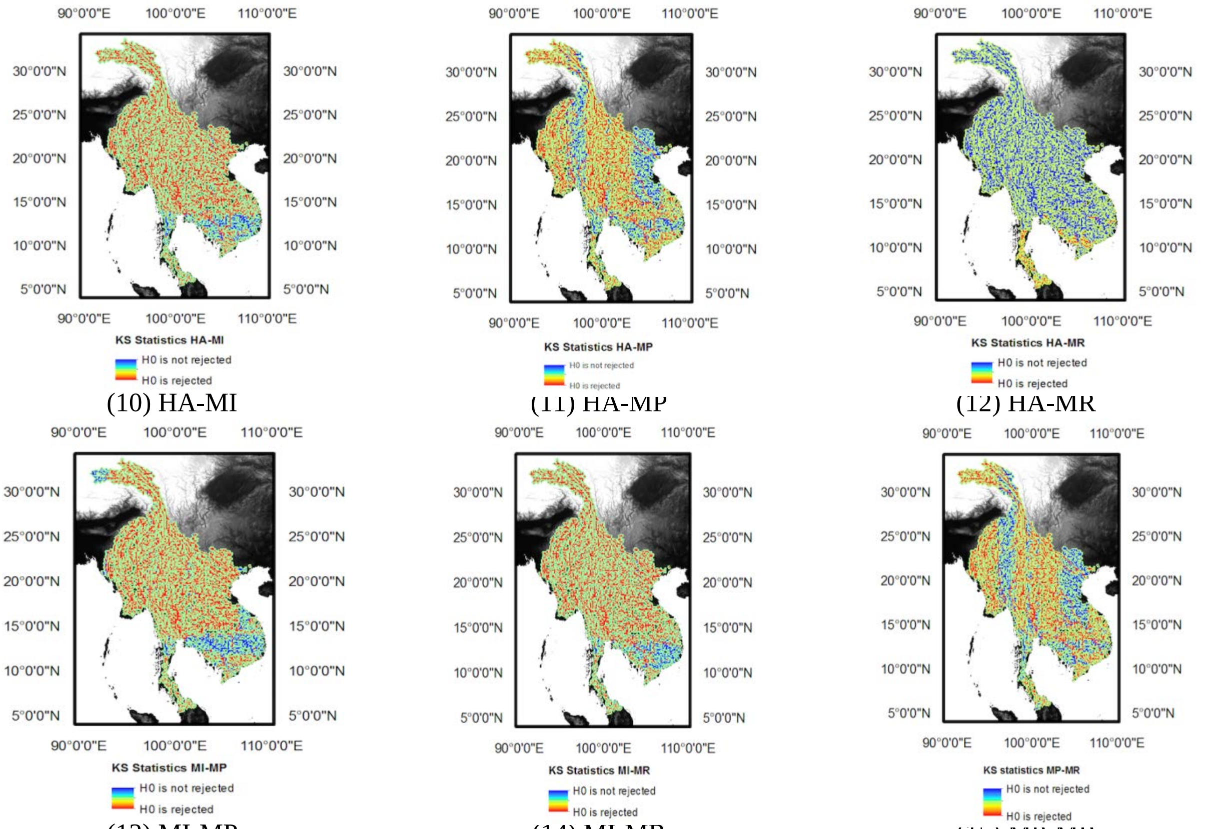
Fig. 2 Geographical distribution of the Kolmogorov-Smirnov test statistics of annual maximum daily discharge for each pair of the d4PDF SST patterns

1.36 at 95% confidence level. According to the equation 2, KS statistics exceeding 0.0641 indicates rejection of the null hypothesis.

Results and discussions

(1) Two-sample Kolmogorov-Smirnov test statistics

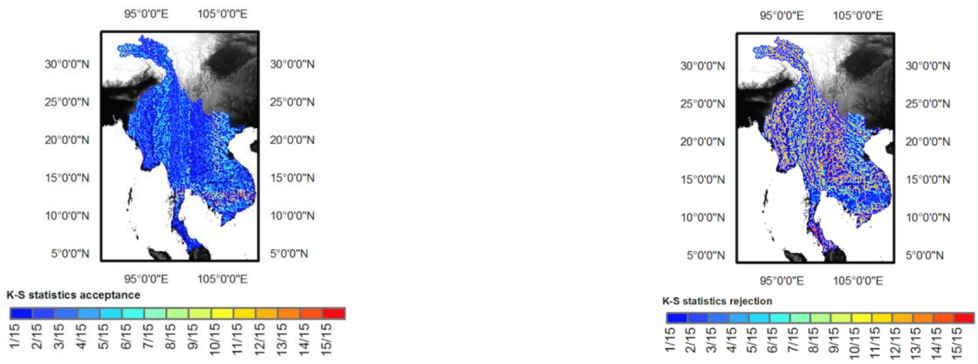
Figure 2 and 3 present geographical distribution of the Kolmogorov-Smirnov statistics (D_n) from 15 groups of the 900-members annual maximum daily discharge of the Indochinese Peninsula of each SST patterns. Statistically significant changes in the probability distribution for each group were calculated at each grid point. On the entire Indochinese Peninsula standpoint, there are only two cases where most of the river basins signal rejection of the null hypothesis. However, On the basins scale, the very clear rejections of the null hypothesis were found at the Irrawaddy, Chao Phraya, and the Mekong River Basin with remarkably similar patterns in12 of 15 groups of SST patterns. Meanwhile, The KS statistics is also high at the Salween River basin, but only reject the null hypothesis in 8 of 15 cases, with



(10) HA-MI (11) HA-MP (12) HA-MR

(13) MI-MP (14) MI-MR (15) MP-MR

Fig. 3 Same as Figure 2 but for the remaining groups of annual maximum daily discharge from d4PDF SST patterns



(a) (b)

Fig. 4 KS statistics evaluation consistency (a) the case of KS statistics null hypothesis acceptance and (b) the case of KS statistics null hypothesis rejection

the other 4 cases indicated the acceptance of the null hypothesis. For parts of Mekong Delta and the southernIndochinese Peninsula, the changes in the probability distribution are found not to be statistically significantin most of the group of d4PDF SST patterns (13-14 cases). The characteristics of change in the probability distributionat the Red River Basin in Vietnam was found having unique pattern, which change of the probability distribution is statistically significant in 7 out of 15 cases. Figure 4a and 4b summarize K-S statistical evaluation consistency of the change in probability distribution of SST-derived annual maximum daily discharge of the Indochinese Peninsula. For the case of hypothesis acceptance, most of the region, except the middle part of Mekong Delta and the Southern Indochina (parts of Phetchaburi River Basin of Thailand), are predicting the significant difference in only 3 to 7 cases of total 15. In contrast, the case of hypothesis rejection,is broadly consistent across the Irrawaddy Basin, the middle part of Mekong Basin, and Chao Phraya River Basin.

The implication of hydrologic analysis for the results in Figure 2,3 and 4 can be summarized as follows:

1) In the region where null hypothesis is ***rejected*** imply that the difference in the prior probability distribution function between the two SST-derived annual maximum daily discharge are significant.Combination of the two rejected datasets could increase the river

discharge projection uncertainty for each particular grid points.

2) In the region where null hypothesis is ***not rejected*** imply the opposite outcome, which means that the difference in the prior probability distribution between the two SST-derived annual maximum daily discharge are not statistically significant. Therefore, the combined ensemble in the non-rejected region should bring more reliable probabilistic projection of the changes in probability density function (PDF) of the annual maximum daily discharge of the Indochinese Peninsula.

This study could potentially be served as a complementary to the past studies (Nakaegawa et al., 2006; Endo et al., 2012; Murakami et al., 2015; Hanittinan et al., 2015), which indicated that the uncertainty of hydro-meteorological data, e.g., precipitation, runoff, and river discharge in terms of total variance due to non-uniform mother population and should underpin the case to combine the datasets that met the criteria set by the aforementioned articles and the one proposed in this study.In addition to the region-wide analysis, results of the KS test to examine statistical difference of the changes in the probability distribution at two selected locations, were also analyzed.

(2) Two-sample Kolmogorov-Smirnov analysis at selected gauging stations

Table 1presents an outcomes of the K-S test at selected locations 1) C.2 station of Chao Phraya Basin and 2) Kampong Chhnang station of Mekong Delta. The results at C.2 station showed that there are4cases of the SST patterns groups that the annual maximum daily discharge projection difference are not statistically significant (CC-MP, CC-MR, GF-MI, HA-MR). Meanwhile, there are 11 possible combinations of the SST patterns that the null hypothesis was rejected (CC-HA, CC-MI, CC-MR, GF-MP, GF-MR,HA-MI, HA-MP, HA-MR, MI-MP, MI-MR, MP-MR). Thereby, the combination of 1800-member ensembles(900 + 900 samples) from the combination between the two SST–derived annual maximum daily discharge at C.2 station could potentially utilized to better construct the probability density function of the annual maximum daily discharge. Meanwhile, much larger numberof samplesup to 3,600-member ensemble of the annual maximum daily discharge (CC-HA-MI-MR) could be used for the same purpose at Kampong Chhnang station.

Table 1K-S statistics evaluation of the null hypothesis at two selected gauging stations (C.2 and Monywa stations)

SST patterns	**KS test statistics (D_n) null hypothesis evaluation**											
	CC		**GF**		**HA**		**MI**		**MP**		**MR**	
	C.2[1]	**K[2]**	**C.2[1]**	**K[2]**	**C.2[1]**	**K[2]**	**C.2[1]**	**K[2]**	**C.2[1]**	**K[2]**	**C.2[1]**	**K[2]**
CC	-	-	✘	✘	✘	✔	✘	✔	✔	✘	✔	✔
GF	✘	✘	-	-	✘	✘	✔	✘	✘	✔	✘	✔
HA	✘	✔	✘	✘	-	-	✘	✔	✘	✔	✔	✔
MI	✘	✔	✔	✘	✘	✔	-	-	✘	✔	✘	✔
MP	✔	✘	✘	✔	✘	✔	✘	✔	-	-	✘	✔
MR	✔	✔	✘	✔	✔	✔	✘	✔	✘	✔	-	-

[1]C.2 = C.2 river gauging station in the Chao Phraya River Basin
[2]K = Kampong Chhnang gauging station in the Mekong Delta
✔= acceptance of the null hypothesis, ✘ = rejection of the null hypothesis

Conclusions

In this study, difference between the two probability distribution function of the annual maximum daily dischargeforced by the total runoff from 15 groups of sea surface temperature patterns, was investigated using the non-parametric, two-sample Kolmogorov-Smirnov test. The Indochinese Peninsula was chosen as the studied area. Application of the two-sample K-S test to the studied area showed that there is significant difference between cumulative probability distribution of the annual maximum daily discharge in most of the SST combinations (12 cases out of 15) at the Irrawaddy River Basin, Chao Phraya River Basin, the middle part of Mekong River Basin, and 8 out of 15 combinations at the Salween Basin. The finding also showed that the difference of the probability distribution at the Mekong Delta and the southern Indochinese Peninsula in Thailand are not statistically significant in most of the SST combination, with only 1-3 cases that the null hypothesis has been rejected.

These findings help clarified that it is possible to increase a number of sample in the future annual extreme river discharge datasets in the Indochinese Peninsula up to multi thousands, which should better derive probability density function and could be useful the hydrological analysis of extreme floods. Future research must also focus on investigating the other hydro-meteorological variables such as precipitation and total runoff to help confirms and explains the characteristics of the detected changes of annual maximum daily discharge of the Indochinese Peninsula.

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