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Ensemble climate projections of mean and extreme rainfall over Vietnam

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ABSTRACT

A systematic ensemble high resolution climate modelling study over Vietnam has been performed using the PRECIS model developed by the Hadley Center in UK. A 5 member subset of the 17-member Perturbed Physics Ensembles (PPE) of the Quantifying Uncertainty in Model Predictions (QUMP) project were simulated and analyzed. The PRECIS model simulations were conducted at a horizontal resolution of 25 km for the baseline period 1961–1990 and a future climate period 2061–2090 under scenario A1B. The results of model simulations show that the model was able to reproduce the mean state of climate over Vietnam when compared to observations. The annual cycles and seasonal averages of precipitation over different sub-regions of Vietnam show the ability of the model in also reproducing the observed peak and magnitude of monthly rainfall. The climate extremes of precipitation were also fairly well captured. Projections of future climate show both increases and decreases in the mean climate over different regions of Vietnam. The analyses of future extreme rainfall using the STARDEX precipitation indices show an increase in 90th percentile precipitation (P90p) over the northern provinces (15–25%) and central highland (5–10%) and over southern Vietnam (up to 5%). The total number of wet days (Prcp) indicates a decrease of about 5–10% all over Vietnam. Consequently, an increase in the wet day rainfall intensity (SDII), is likely inferring that the projected rainfall would be much more severe and intense which have the potential to cause flooding in some regions. Risks due to extreme drought also exist in other regions where the number of wet days decreases. In addition, the maximum 5 day consecutive rainfall (R5d) increases by 20–25% over northern Vietnam but decreases in a similar range over the central and southern Vietnam.
These results have strong implications for the management water resources, agriculture, bio diversity and economy and serve as some useful findings to be considered by the policy makers within a wider range of climate uncertainties.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that global surface temperatures may rise to about 1–2 °C by the year 2050 and to about 2–5 °C by the end of the 21st century, depending on how much of the anthropogenic Green House Gases (GHG) will be emitted to the atmosphere in the coming decades. The latest findings from the IPCC show many evidences that climate change has already affected many regions in Southeast Asia, one of the highly climate vulnerable regions in the world (IPCC, 2007, 2013). It is high time that more research into climate science is necessary as far as Southeast Asia is concerned, not just in understanding the climate and its change but also be able to understand the climate impacts and its severity so that all countries in Southeast Asia can prepare themselves adequately to adapt to such changes.

The IPCC's Fifth Assessment Report (AR5) mentioned that significant changes in rainfall patterns and increased global sea-level rise may be expected by 2100 (IPCC, 2013). The report also mentioned that it is certain that global mean surface temperature has increased since the late 19th century and the decade of the 2000′s has been the warmest with the global combined land and ocean temperature data showing an increase of about 0.89 °C during the period 1901–2012. With respect to precipitation changes, the report indicated that future increases in precipitation extremes related to monsoons is very likely in South America, Africa, East Asia, South Asia, Australia and Southeast Asia. Temperatures are likely to increase by 3 °C and rainfall increases up to 40% are also likely by the end of the century, over Southeast Asia. Overall, many of the reported climatic changes and projections have been found to be consistent with its earlier assessment report AR4 (IPCC, 2013).

These climatic changes are significant as most of the economically weaker countries in Southeast Asia are highly vulnerable to climate change and are in need of both scientific expertise and the economic means to combat climate change (ADB, 2009). Over the past two decades, decreasing trends in precipitation as well as rising trends in sea

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level (1–3 mm/year) have also been noted. The number of extreme weather events such as hot days/warm nights or number of heavy storm events and tropical cyclones has also increased. These climate changes have shown impacts on other physical systems - increasing temperatures and increasing extreme weather events also led to the decline of crop yield in many Southeast Asian countries (Thailand, Vietnam and Indonesia), massive flooding in Hanoi, Hue (Vietnam), Jakarta (Indonesia), Vientiane (Laos) and landslides in Philippines and droughts in many other parts of the region (ADB, 2009). Water shortage, agriculture constrains, food security, infectious diseases, forest fires and degradation of coastal and marine resources have also been increasing (IPCC, 2007). The strongest and most consistent increases are seen over northern Indonesia, Singapore and Malaysia in June, July, August (JJA) and over southern Indonesia and Papua New Guinea in December, January, February (DJF). Some other studies (Kharin et al., 2007; Lenderink and Van Meijgaard, 2008) have also shown that precipitation extremes are expected to increase both in intensity and frequency over many regions in the world due to global warming.

In this context of climate change over Southeast Asia, the PRECIS (Providing Regional Climates for Impacts Studies) regional climate model was used in this study to assess future climate changes in rainfall over Vietnam. PRECIS was developed by the Hadley Center in UK and has been used in various regional climate studies around the globe. Rao et al. (2014) applied PRECIS model to assess the mean and extremes of rainfall over India for a suit of 5 ensemble PPE boundary conditions. They found out that changes in extreme rainfall events and dry spells suggesting not only shifts but also substantial increase in the spread of the precipitation distribution, with an increased probability of the occurrence of events conducive to both floods and droughts. Kumar et al. (2011) performed simulations from a 17-member Perturbed Physics Ensemble (PPE) generated using the Hadley Center Coupled Model (HadCM3) for the "Quantifying Uncertainty in Model Predictions" (QUMP) project which were used to drive the PRECIS for period of 1961–2098. The model showed reasonable skill in simulating the monsoon climate over India. The authors reported that the summer monsoon rainfall over India was expected to increase by 15% in the 2080s compared to the baseline period. In addition, the rainy days were projected to be less frequent and more intense over central India. Alves and Marengo (2010) used the PRECIS to evaluate the accuracy and skill in describing the seasonal variability of the main climatological features over South America and adjacent oceans in their 30 year (1961–1990) simulations. It was reported by the authors that precipitation and temperature patterns as well as the main general circulation features were well simulated by the model. In another study, Marengo et al. (2009) also used the PRECIS model to analyze the distribution of extremes of temperature and precipitation in South America over the past (1961–1990) and in the future (2071–2100) climate under the IPCC A2 and B2 emissions scenarios. It was shown that the PRECIS model was able to reproduce the spatial and temporal patterns of precipitation and temperature and the main features of the large circulation reasonably well. It was reported that these trends were consistent with those from the GCM HadAM3P model that was used to drive PRECIS and some detailed climatic features were captured at finer scales than those resolved by the global model. The study suggested that the model simulated the spatial distribution of extreme temperature and rainfall events well enough although temperature distributions were more realistic than rainfall. This finding along with the others mentioned earlier also indicated that compared to temperatures, precipitation is a difficult variable to be simulated accurately due to its large variability in space and time. Other studies that have applied PRECIS are those of Karmalkar et al. (2011), Duliere et al. (2011), Mileham et al. (2009), Islam et al. (2009), Bloom et al. (2008), Buonomo et al. (2007) and Kumar et al. (2006), to name a few.

Very few climate change studies exist over Vietnam. McSweeney et al. (2012) applied the 17-member PPE in developing high resolution climate scenarios over Vietnam using a subset of 5 ensemble members

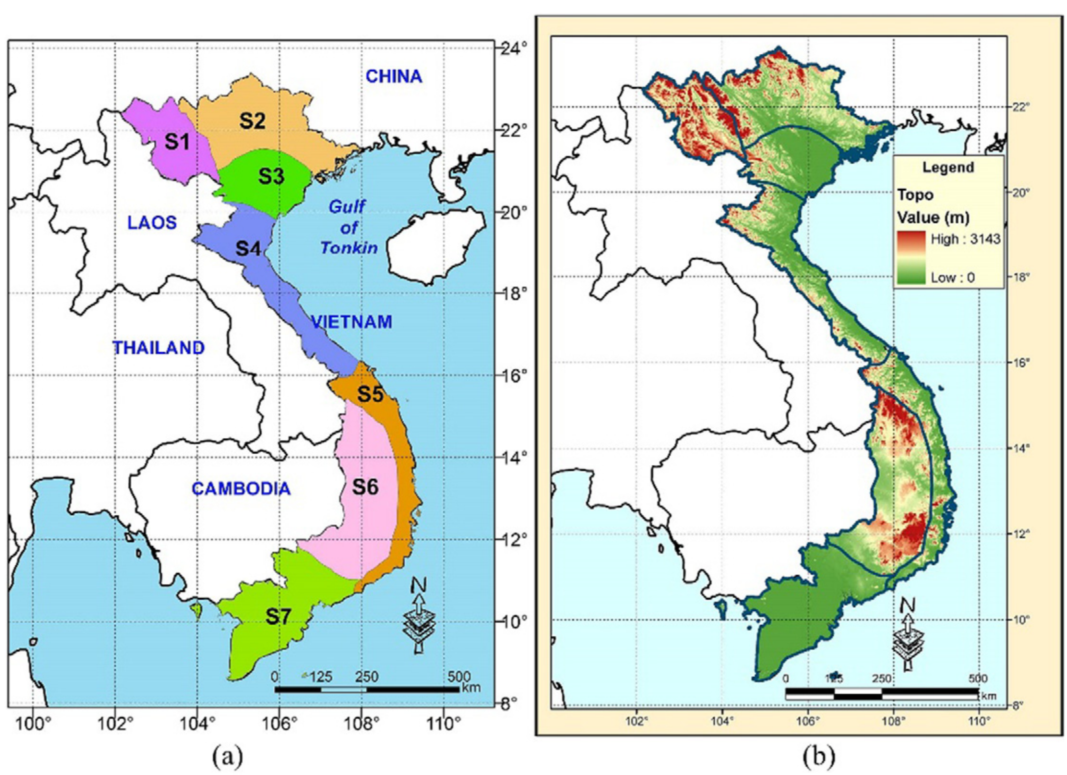

Fig. 1. (a) Seven climate sub-regions of Vietnam, (b) Vietnam topography by SRTM.

Table 1
Climate sub-region of Vietnam.

Sub-region climate	Name
Northwest	S1
Northeast	S2
Red River Delta	S3
North Central	S4
South Central	S5
Central Highland	S6
South	S7

to study summer monsoon. Mai et al. (2014) later projected the changing climate using the PRECIS model using the 5 member QUMP subset recommended by McSweeney et al. (2012) to characterize the mean precipitation, surface temperature and 850 hPa wind speed/wind direction over Vietnam. They concluded that the 5 member PPE demonstrated errors with similar characteristics to the ERA-Interim-driven simulations, although with differences in the magnitude of those errors that may have arisen due to the characteristics of the different members of the HadCM3-based PPE. Ho et al. (2011) used the regional climate model RegCM3 to assess future climate changes over the mid-century driven by the GCM CCSM3.0, forced under the IPCC future A1B emission scenario over Vietnam. Their study revealed an increase in the summer temperatures and a decrease in number of colder nights over Vietnam. The authors found out that the rainy season heavy rainfall events tend to decrease for all sub-regions except over northwest and south-central Vietnam. In a different study, the Ministry of Natural Resources and Environment (MONRE) of Vietnam conducted a study using a climate scenario generator and projected some seasonal changes in future climate over the period 2090–2100 relative to the 1980–1999 period. The projections were estimated for some main climatic zones over Vietnam: North, Center, Highland and South. This study reported increasing temperatures during summer and winter seasons and increases (decreases) in rainfall increases during JJA (DJF) season (MONRE, 2009).

The objective of this paper is to assess changes in the future climate over Vietnam, using the PRECIS model, with a focus on mean and extreme precipitation.

2. Model, study region and data

2.1. Study region and observation data

Vietnam is located in Southeast Asia, bounded between the latitudes 8°N and 23°N and longitudes of 102°E and 109°E. The coast line of 3260 km covers the East and the South of Vietnam. Three-fourths of Vietnam's territory is covered by mountains and hills with the highest peaks of >3000 m. Based on the topography and geography, Nguyen and Nguyen (2004) characterized Vietnam into 7 climate sub-regions from North to South of Vietnam that has been widely accepted by the Vietnam climate community and in the studies of MONRE, 2009; Ho et al., 2011; Phan et al., 2009.

In this study, we apply the same 7 climate sub-regions as Nguyen and Nguyen (2004), shown in Fig. 1(a) and marked S1 to S7 (Sub-region 1 to 7). The regions are listed in Table 1. The topographical features over Vietnam, taken from the SRTM (Shuttle Radar Topography Mission) dataset, are displayed in Fig. 1(b). As seen in Fig. 1, sub-regions S1, S2 and S6 have high topography while S3 and S7 are the delta areas with very low elevation.

Table 2
Five members PPE selected for high resolution climate PRECIS model for Vietnam.

Ensemble Member	Sensitivities
Q0	Unperturbed model
Q3	Low sensitivity rainfall
Q10	Large increase in wet-season rainfall over Vietnam
Q11	Large decrease in wet-season rainfall over Vietnam
Q13	High sensitivity rainfall

Table 3
STARDEX Precipitation indices used to assess rainfall extremes.

Indices	Description	Unit
P90p	90th percentile of rainfall	mm/d
Prcp	Total number of rain days per year	%
R5d	Maximum 5-day accumulated precipitation	mm
SDII	Mean wet day rainfall intensity	mm/d

The APHRODITE dataset (Asian Precipitation Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources) was used as the reference (observed) data in this study. The APHRODITE project developed state-of-the-art daily precipitation datasets at high-resolution grids (0.25° and 0.5°) for Monsoon Asia. This study uses the 0.25° dataset of the Monsoon Asia region for the period 1961–1990. The datasets were produced using data obtained from rain gauge observations network. The basic algorithm that was adopted is documented by Xie et al. (2007). This dataset of precipitation is available on a daily scale, only for all land areas covering Monsoon Asia and not available for oceanic areas. Further details can be obtained at http://www.chikyu.ac.jp/precip/ and from Yatagai et al. (2009, 2012). This dataset is referred to as 'APH', in this paper, for brevity.

2.2. PRECIS model

PRECIS is a regional climate modelling tool that can be applied over any area of the globe on a relatively inexpensive, fast personal computer to provide regional climate information for impacts studies. The RCM PRECIS is based on the atmospheric component HadAM3P of the GCM HadCM3 with substantial modifications to the model physics. Many physical processes such as the dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and the deep soil are configured in the model. The model was simulated at a 25 km resolution in this study. The PRECIS model has been documented in detail by Jones et al. (2004) and is available from the PRECIS website: http://precis.metoffice.com/.

The Perturbed Physics approach was developed by the Hadley Center in order to assess uncertainties in climate projections (McSweeney and Jones, 2010). The perturbed physics ensemble consists of a single model structure and making perturbations to the values of parameters in the model (Kumar et al., 2011). Boundary data from a 17-member HadCM3 PPE under A1B scenario are available at the Met Office and have been named from 'Q0 to Q16', in which Q0 is the standard run without perturbation whereas the other 16 members are the perturbed ensemble runs. Five members (Q0, Q3, Q10, Q10 and Q13) out of the seventeen members PPE from the QUMP project have been utilized in this study, following the recommendations made by McSweeney et al. (2012). A short description of the selected 5 members is given in Table 2. The PRECIS model simulations in this study comprised the baseline period from 1961 to 1990 and a future period 2060–2099 at a spatial resolution of 25 km, driven by the boundaries of the selected 5 member QUMP subset.

3. Methodology

The mean seasonal precipitation climatology was calculated for annual, northeast monsoon (DJF: Dec, Jan, Feb), southwest monsoon (JJA: Jun, Jul, Aug) periods for both the model results and observations in order to evaluate the ability of the PRECIS model in simulating the mean climate of the region. Both observations and models have the

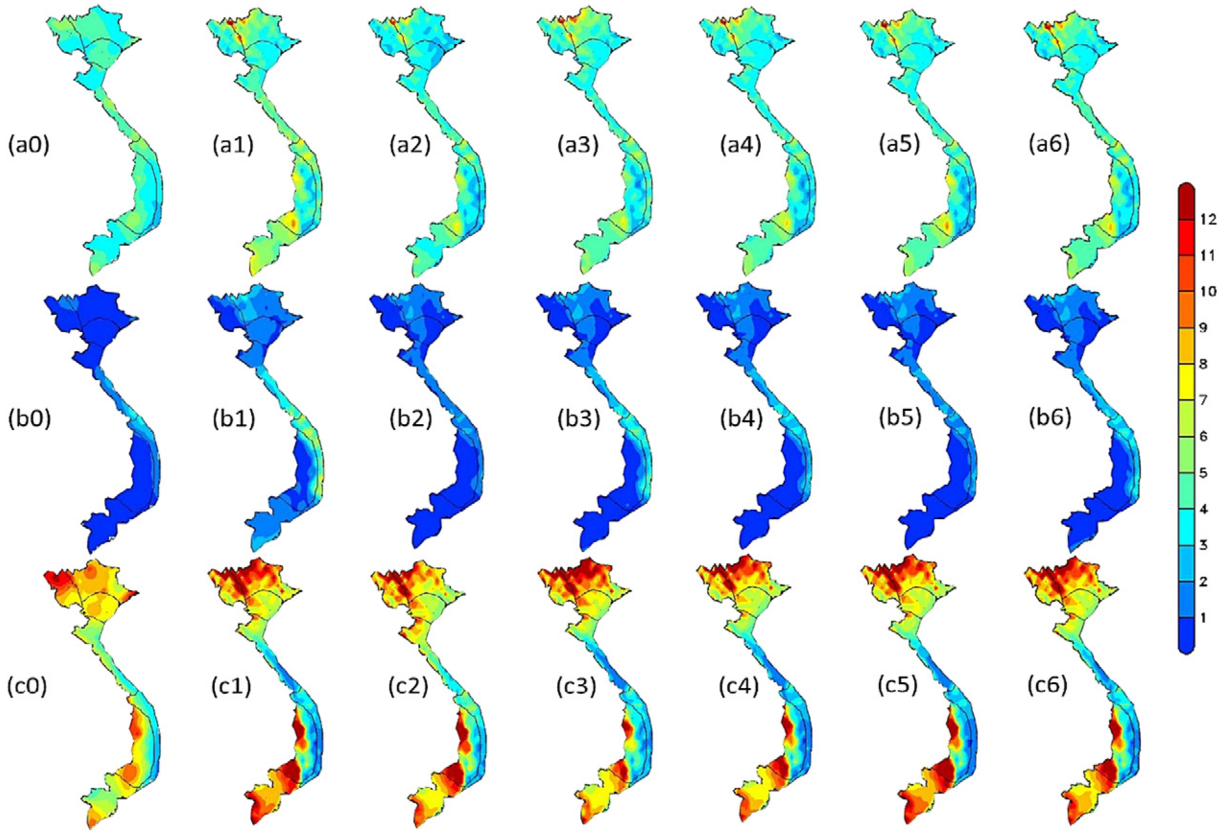

Fig. 2. Mean climatological rainfall (a) annual; (b) northeast monsoon (DJF); (c) southwest monsoon (JJA); (0) APH; (1) Q0; (2) Q3; (3) Q10; (4) Q11; (5) Q13; (6) ensemble.

same spatial resolution of 25 km. The areal average monthly climatology has been calculated for different climate sub-regions and also displayed as annual cycles. This is to ensure that the model simulations are able to capture the peaks as well as the magnitude of monthly rainfall over all 7 sub-regions.

One of the ways to characterize climate variability and extremes is to calculate climate indices based on daily time series of basic variables such as temperature and precipitation. This allows a preliminary assessment of the ability of the RCM driven using reanalyses to capture the main weather meteorological sequences, through four indices dealing

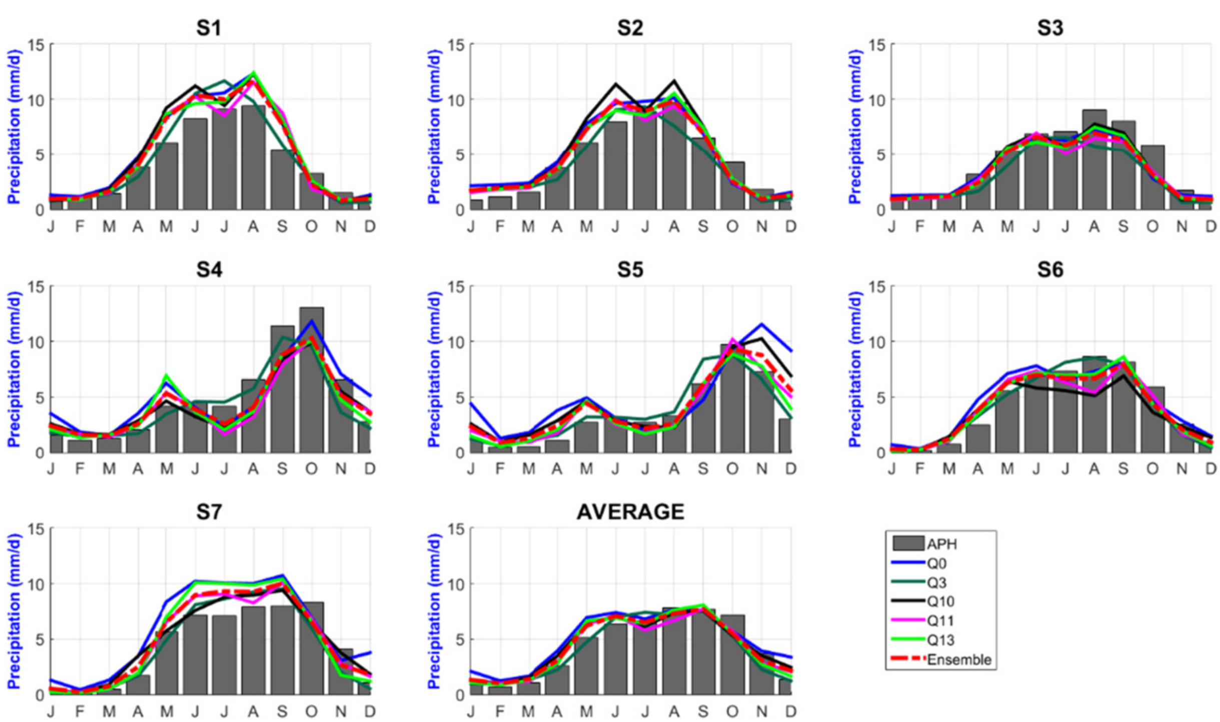

Fig. 3. Annual cycle of rainfall for all sub-regions over Vietnam.

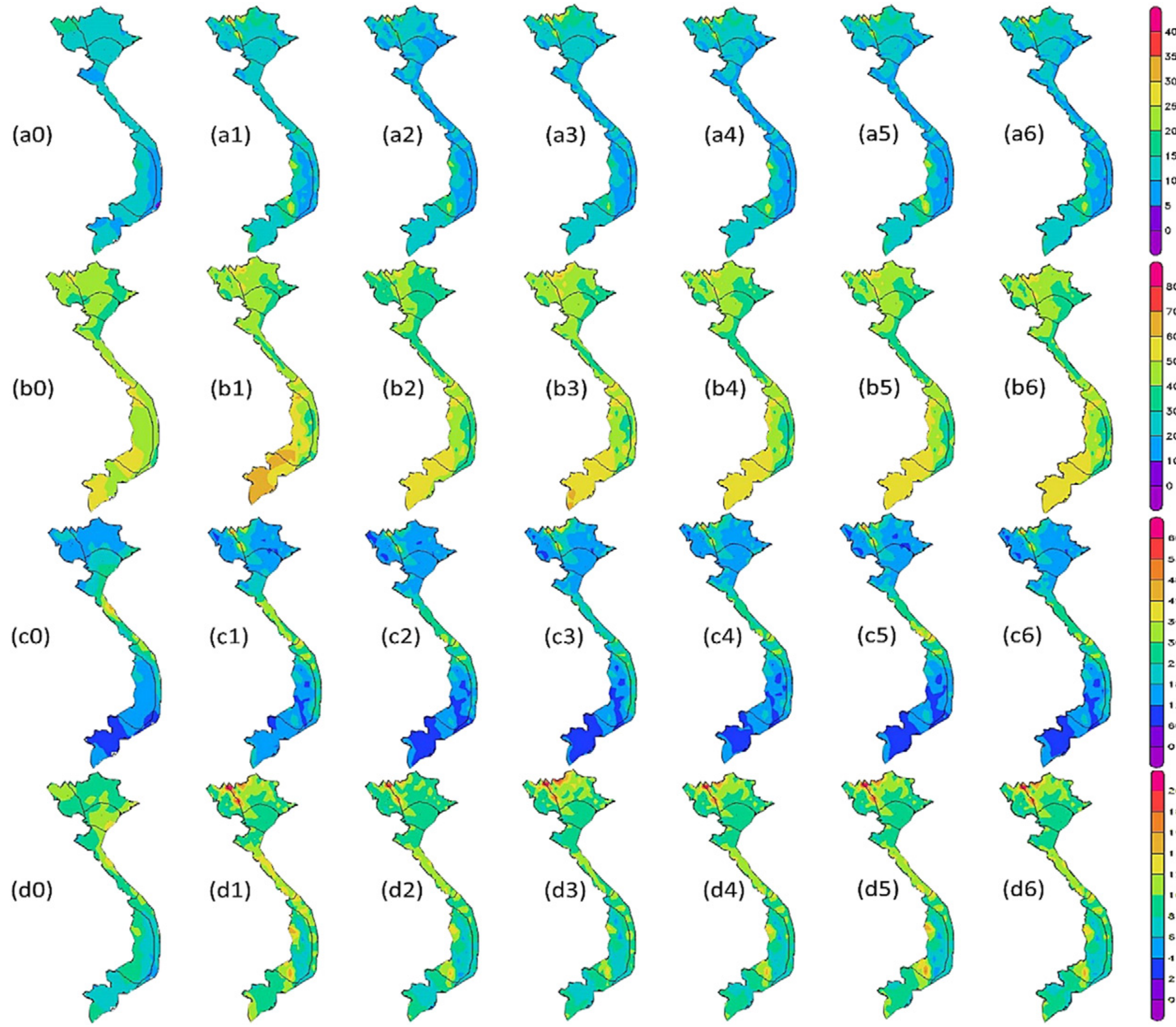

Fig. 4. Mean precipitation indices (a) P90p (mm/d); (b) Prcp (%); (c) R5d (mm); (d) SDII (mm/d); (0) APH; (1) Q0; (2) Q3; (3) Q10; (4) Q11; (5) Q13; (6) ensemble.

with occurrence, duration and intensity of precipitation events (i.e. number of wet days, mean intensity per wet day, maximum 5-days amount, and the 90th percentile of daily rainfall). These indices are used by several international research groups who have developed a standard methodology for calculating such indices, as found in: ETCCDMI -Expert Team on Climate Change Detection and Indices, http://cccma.seos.uvic.ca/ETCCDMI/index.shtml and in the European research project known as STARDEX -Statistical and Regional dynamical Downscaling of Extremes for European regions- www.cru.uea.ac.uk/cru/projects/stardex.

The frequency and intensity of extreme precipitation events are important metrics to be studied as it is very common for climate impact studies to use the output of the regional climate models for further downstream applications such as hydrology or crop studies. To this end, we apply some metrics of the STARDEX project for evaluating precipitation extremes. The following 4 indices were chosen for this purpose: P90p (90th percentile precipitation), Prcp (total number of annual wet days >1 mm), R5d (Max 5 day accumulated rainfall) and SDII (wet day rainfall intensity). These precipitation indices are tabulated in Table 3.

The above selected 4 indices were calculated using daily data from PRECIS model outputs and compared against APH (daily) observed data. This comparison has been made for the baseline period 1961–1990 utilizing only the land only grids from the model simulations over Vietnam. The future climate changes have been assessed using the climate simulations of the future period (2061–2090) of the 5 member QUMP subset, relative to the baseline period (1961–1990).

4. Results and discussions

4.1. Mean seasonal precipitation

It is common procedure to evaluate model simulations against observations for the baseline period (1961–1990), before assessing the model simulated future projections. For doing this, the APH dataset was used as the reference observation against the 5 member PRECIS model ensemble, PPE. The evaluation was performed over 3 time scales, Annual, Northeast monsoon (DJF) and Southwest monsoon (JJA) and are shown in Fig. 2(a), (b) and (c), respectively.

In the figures, the digit '0' denotes APH and '6' denotes the 'ensemble' (average of the 5 member PPE) and the digits '1' to '5' are for each ensemble member Q0, Q3, Q10, Q11, Q13, respectively. The observed data APH in Fig. 2(a) shows that the mean precipitation on the annual scale ranges from 3 to 7 mm/day. The APH mean precipitation also indicates a dry season during the northeast monsoon (1–3 mm/day) and a very wet season during the southwest monsoon

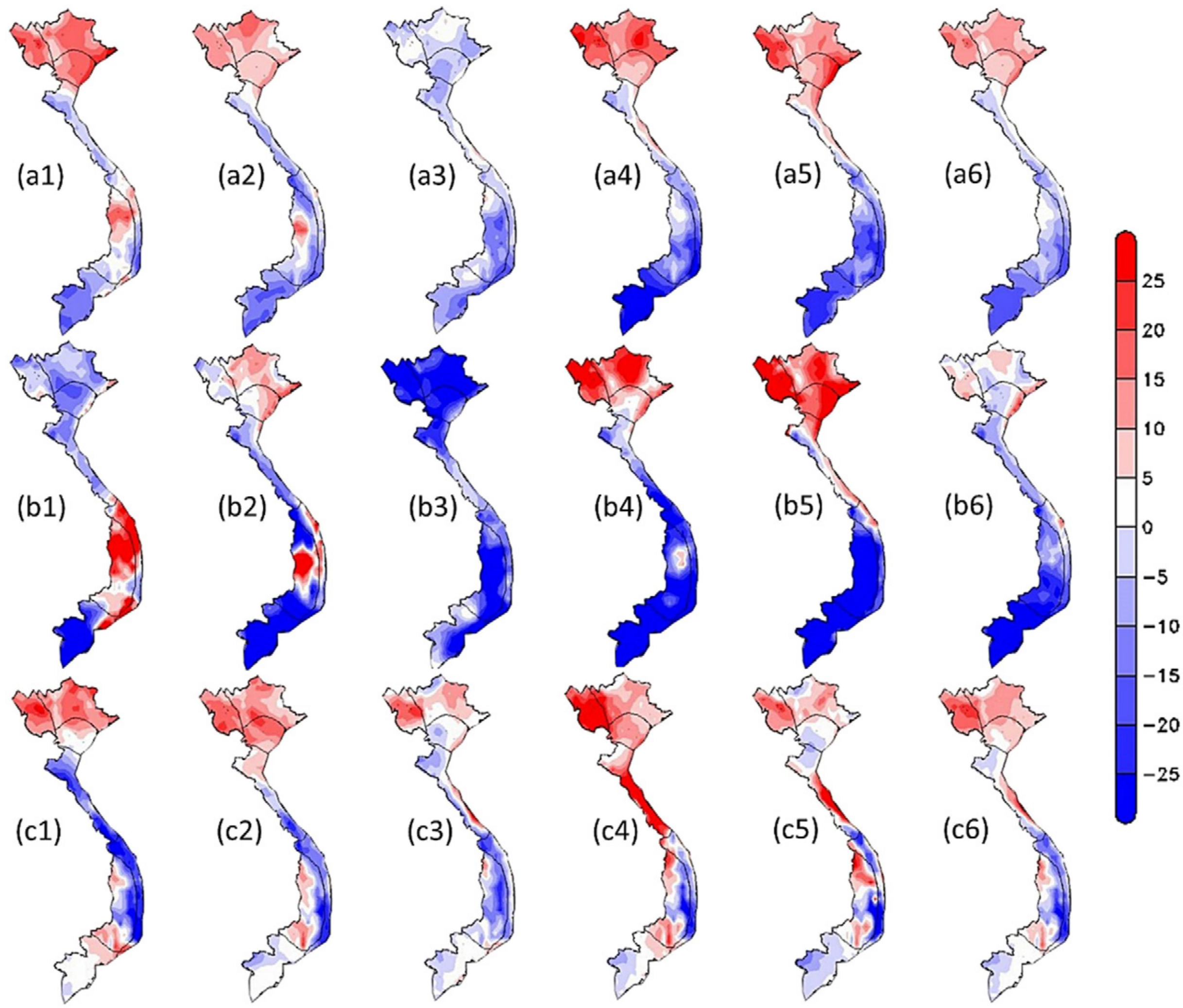

Fig. 5. Relative anomaly (%) seasonal precipitation 2060–2089 with reference to baseline 1960–1989 (a) annual; (b) northeast monsoon (DJF); (c) southwest monsoon (JJA); (1) Q0; (2) Q3; (3) Q10; (4) Q11; (5) Q13; (6) ensemble.

(7–12 mm/day). This observed feature is reproduced in all the 5 PPE datasets from Q0 to Q13 and hence, in the 'grand ensemble'. During the annual and the southwest monsoon periods, the PPE overestimates the APH in the sub-region S1, S2, S6 and S7. It is perhaps due to the high topography that the model is able to resolve at this 25 km resolution. During the northeast monsoon, Q0, Q10, Q11 overestimate the S3 and S4 sub-regions by about 2–3 mm while Q3 and Q13 underestimate observations by 1–2 mm. By spatial distributions of rainfall, Q3 agrees well with the APH observations for all seasons.

In order to evaluate the annual cycle of rainfall over different climatic sub-regions, Fig. 3 displays the 7 sub-regions and their areal average annual cycle of precipitation. The bar chart represents the APH dataset while the line graphs are for the 5 member PPE and the ensemble. The patterns of the annual cycles show that S1, S2, S3 and S6 have 1 peak rainfall in August while there are 2 peaks for S4 and S5. On the other hand, S7 exhibits similar rainfall during the summer monsoon season from June through to October. Amongst all PPE members, Q13 is able to reproduce the annual cycle of all sub-regions while Q10 performs the least in comparison. There is general overestimation by the PPE in the magnitudes of precipitation for S1, S2 and S7 regions while S3 shows underestimation. In general, Q3 best describes the observations in spatial scale while Q13 shows the best match in the temporal scale.

4.2. Precipitation indices

This section makes an assessment of the various STARDEX precipitation indices between observed data APH and the model simulations, over the baseline period 1961–1990.

The 90th percentile rainfall (P90p) was calculated by ranking the 90th percentile on the accumulation time series of wet day for each year. This index was used to assess extreme precipitation. The spatial distributions of P90p are displayed in Fig. 4(a). It is seen that the simulations compare well against APH observations for high rainfall distributions and their quantities. The model overestimates the magnitude of rainfall over parts of the mountainous regions in S1, S2 and S6, due to very complex topography. This topographical influence can be compared against the map shown in Fig. 1.

The total number of annual wet days 'Prcp' (units in %) was also evaluated. The rainy days over Vietnam generally have an average of 30–60% of the annual rainfall (MONRE, 2009). The model simulations show that there are more wet days over the southern part of Vietnam

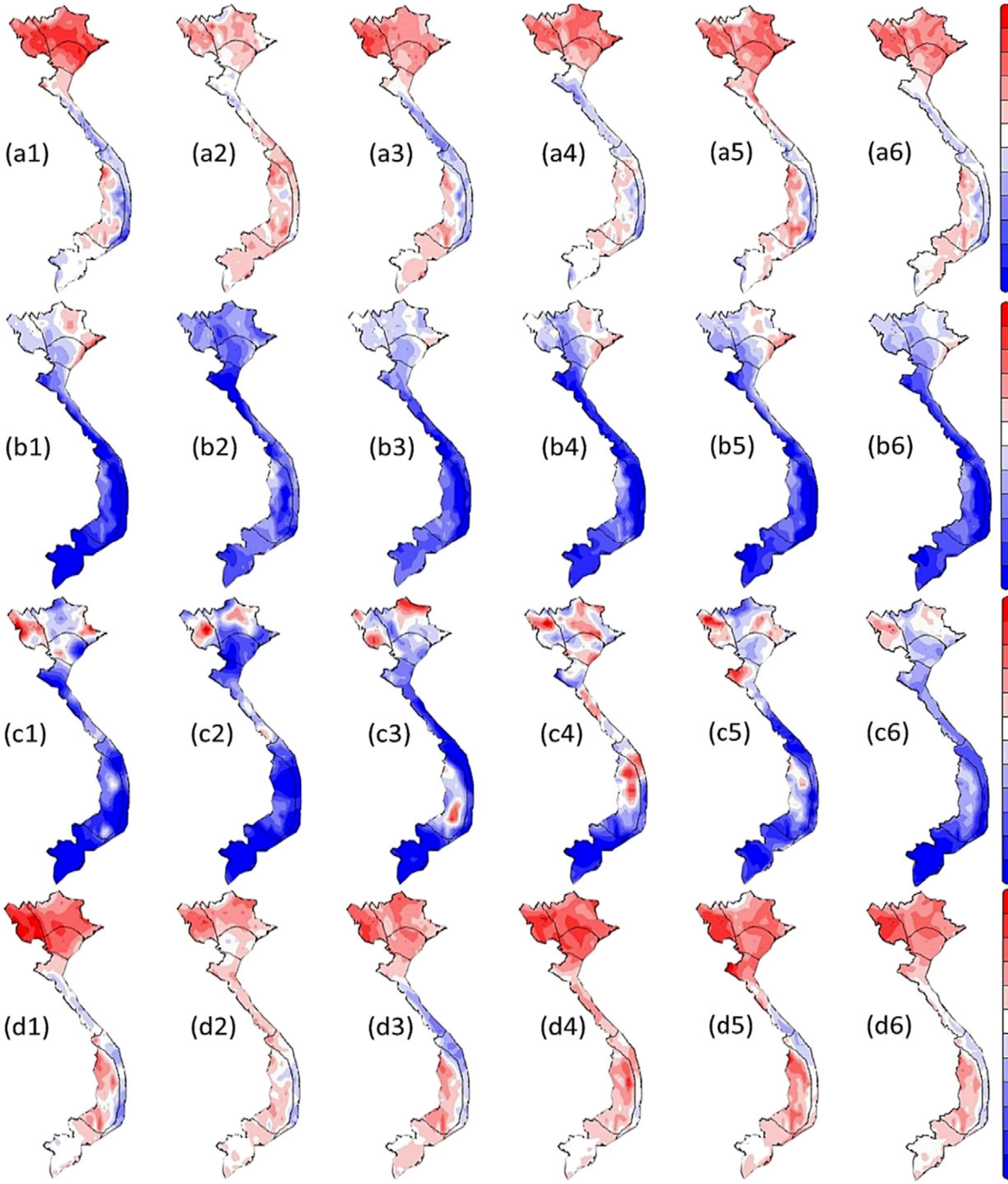

Fig. 6. Relative anomaly (%) precipitation indices 2060–2089 with reference to baseline 1960–1989 (a) P90p; (b) Prcp; (c) R5d; (d) SDII; (1) Q0; (2) Q3; (3) Q10; (4) Q11; (5) Q13; (6) ensemble.

(S6, S7) compared to the north. S7 is the sub-region which has the highest number of wet days (50–60%) while S1, S2 and S3 have the least wet days (30–40%) compared to the other sub regions. The APH observations also support this feature.

The maximum accumulated 5-day rainfall amount (R5d) index was also calculated as this is crucial over the region, being affected by heavy rainfall induced flooding (Fig. 4(c)). The center of Vietnam (S4 and S5) has always been affected by flooding due to annual storms coming into Vietnam (MONRE, 2009). The R5d index shows that the highest long duration rainfall is observed in sub-region S4 and north of S5, of about 300 mm per 5 days. This can be seen in both observations and simulations for the baseline period, except for the simulation by Q10 (underestimation, as seen in Fig. 4(c3)).

The mean rainfall intensity for wet day index, otherwise the simple daily intensity index (SDII) is shown in Fig. 4(d). Similar to R5d, high SDII index can be found in the S4 sub-region. However, the models do not reproduce the observed high SDII in S3. Moreover, the models simulate higher rainfall magnitudes over S1 and S2 sub-regions. However, S4 and S7 are in good agreement with the observation.

A detailed evaluation of these PRECIS model simulations has been described by Vu (2013) and only a bird's eye-view of these

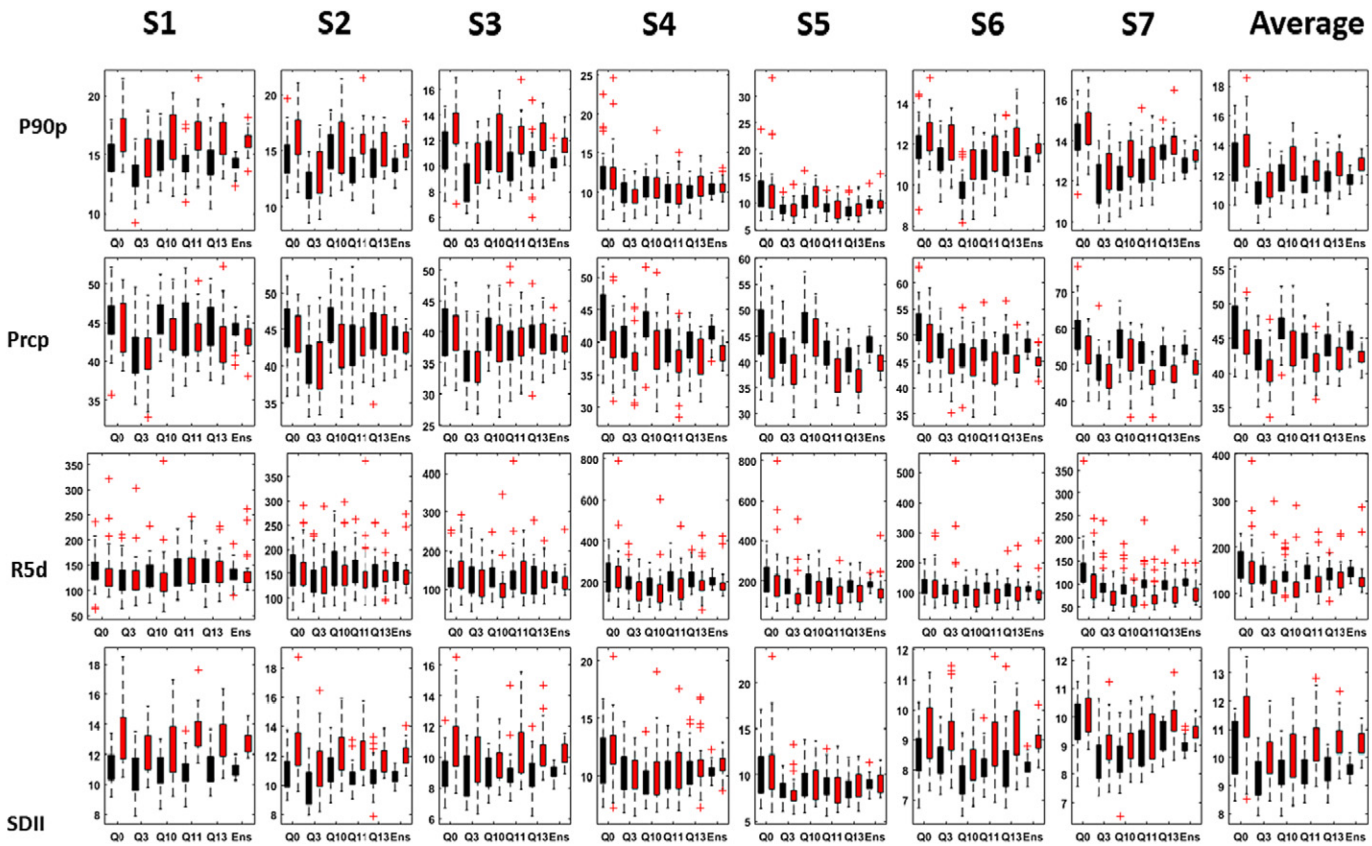

Fig. 7. Box-plots precipitation indices for baseline (1960–1989 - black) and projection future climate A1B (2060–2089 - red), 5 member PPE and ensemble for all climate sub-regions over Vietnam.

evaluations are presented in this paper as the focus is only on mean and extreme rainfall.

4.3. Change in mean seasonal precipitation: Future climate projections

The anomaly (difference between the future and present) of the mean seasonal precipitation of 2061–2090 relative to 1961–1990 are calculated in percentages and displayed in Fig. 5.

The changes for the annual and the seasonal mean rainfall for all five members are shown. On an annual scale, all PRECIS simulations suggest that S1, S2 and S3 are likely to see an increase of 10–20%, except Q10 (Fig. 5(a3)), while there is a decreasing trend over central and southern Vietnam (S4, S5, S6 and S7), except Q0 and Q3 (slight increasing in S6). Model simulations also indicate that the northeast monsoon is likely to experience the highest decrease in seasonal rainfall of up to 25% over most of the central to the southern regions of Vietnam, except for Q0 and Q3 (increasing in S5, S6). The southwest monsoon shows similar trends, as that of the annual scale, with increasing rainfall in the northern regions (S1, S2 and S3). Overall, the grand ensemble shows that there is an increase in the northern Vietnam rainfall by 10–20% and a decrease over central and southern Vietnam by 5–15%.

4.4. Change in precipitation extremes

The change in extreme precipitation was assessed by calculating the relative anomaly of the STARDEX indices, shown in Fig. 6. The P90p in Fig. 6(a) shows an overall increase in extreme rainfall over the northern regions (S1, S2 and S3) and central highland, S6. Mixed changes are seen for regions S4, S5 and S7. The ensemble member Q3 (Fig. 6(a2)) depicts an opposite signal of P90p in S5 compared to the rest. The ensemble mean (Fig. 6(a6)) shows that the increase in the 90th percentile of maximum rainfall is 10–20% for S1, S2, S3 and S6 and 5% for S7. However, the P90p decreases by 5–10%, over S4 and S7.

The anomaly of total number of rain days shows strong decreases, as seen in Fig. 6(b). The overall decrease is about 5–10% with marginal increases observed for S2 and S3 in Q0, Q11, and Q13.

The R5d index also shows more decreases for the 5 ensembles. Subregions S1 and S2 agree in the increasing signal for all ensembles while the rest of the sub-regions suggest decreases by 10–20%. Only Q11 (Fig. 6(c4)) shows increases over S4, S5 and S6.

With the overall increase in maximum precipitation index P90p and a decrease in the total rain day Prcp, it can be implied that the mean rainfall intensity index SDII is expected to increase. This can be confirmed using Fig. 6(d) where most of the sub-regions are expected to experience increases in SDII index by 10–25%. This also implies that an increase in SDII index might lead to heavy rainfall induced flooding in most of the regions. Q11, in Fig. 6(d4), shows an overall increment in SDII index for the whole country. However, the ensemble simulation in Fig. 6(d6) points out that there is a marginal decrease in the rainfall intensity, over S4 and S5.

4.5. Comparison of the baseline and projected precipitation indices

The baseline (1961–1990) and projected (2061–2090) precipitation indices are displayed as box plots in Fig. 7, for all sub-regions. The black color depicts the baseline period and red color displays the projection for the same member, which enables the changes, from baseline to projections, to be seen clearly.

The 90th percentile (extreme rainfall) changes suggest that regions S1, S2, S3, S6 and S7 might experience large increases and variability while over regions S4 and S5, the changes are not pronounced. The number of wet days (Prcp) suggests that almost all regions might experience a decrease in the wet day frequency in the future. The 5 day rainfall shows decreases over most of the sub regions only with Q0 showing increases in region S3. The rain intensity, however, suggests strong increases in almost all 7 sub regions. These signals are more pronounced and also indicate larger variability in regions S1, S2, S3, S6 and S7 than S4 and S5.

5. Conclusions

A 5 member subset of the 17 member PRECIS QUMP (HadCM3 A1B) ensemble was used to evaluate the baseline (1961–1990) and future climate projections (2061–2090) in the mean and extreme precipitation regimes over seven climatic sub-regions of Vietnam. The 5 member ensemble exhibits good skills in reproducing the observed spatial pattern of mean seasonal rainfall and the annual cycle, by capturing the peaks and magnitudes of rainfall for all sub-regions and the extremes. The extreme precipitation was evaluated based on the STARDEX precipitation indices. Assessment of the future climate change suggests that there is a substantial increase in the northern and central highland sub-regions of Vietnam during the annual and southwest monsoon season rainfall with marginal decreases over central and southern Vietnam. Further analyses on extreme precipitation reveals that the 90th percentile of rainfall and daily rainfall intensity increase by 10–20% over the northern and central highlands but show decreases over central Vietnam. This has implications for climate adaptation as there is a potential risk for heavy rainfall induced flash floods in the mountainous regions of Vietnam under a changing climate. The total number of wet days decreases spatially from the center towards the south of Vietnam, by 5–10%. The maximum 5 day accumulated rainfall exhibits increases in the mountainous region of northern Vietnam by 20% and decreases from the central to southern Vietnam by 10–20%.

We infer that with strong increases in rainfall, implications to floods exist, but some decreases and potential risks to droughts in the future cannot be ruled out. Adaptation strategies are quite necessary and need to be re-visited by planners and policy makers depending on what crucial factors may be native to those sub-regions, such as irrigation, hydropower, bio-diversity or infrastructure. This study is a contribution to the climate science over Vietnam and these initial findings and trends are yet useful indicators of large changes that are likely in an uncertain future.

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