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Multi-year variability or unidirectional trends? Mapping long-term precipitation and temperature changes in continental Southeast Asia using PRECIS regional climate model

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Abstract: The subject of change detection in climate time series has recently received greater interest as the perception of a human-induced change in the climate is now widely accepted. However, changes in regional precipitation and temperature remain uncertain. This study characterizes projected fine-scale changes in precipitation and temperature in continental Southeast Asia over the period 1960-2049. Twenty four annual variables were derived from grid-based daily precipitation and temperature produced by the PRECIS regional climate model under A2 and B2 scenarios. These time series, capturing precipitation intensities (classified as low, medium and high), seasonality and extremes in precipitation and temperature, were subjected to the modified Mann-Kendall trend detection test accounting for long-term persistence. The results indicate that temperature increases over the whole region with steeper trends in higher latitudes. Increases in annual precipitation, mainly restricted to Myanmar and the Gulf of Thailand, result from increases in high precipitation during the wet season. Decreases are observed mainly over the sea and caused by a reduction of low precipitation. Changes in the occurrence of the monsoon affect the low-latitude sea areas only. By showing that significant precipitation change are minor over land areas, these results challenge most of the previous studies that suggested significant precipitation changes over Southeast Asia, often mixing up multi-decadal variability and long-term unidirectional trends. Significant changes in precipitation and temperature may induce higher agricultural yields as steepest temperature and precipitation increases will predominantly affect the coldest and driest land areas of the region.

Key words: climate change, climate variability, monsoon, Mann-Kendall, scaling effect, Southeast Asia

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1. Introduction

It is now widely accepted that recent global warming is influenced by the human-induced increases in greenhouse gas emissions to the atmosphere (Lashof and Ahuja 1990; IPCC 2007). Its impact on precipitation and temperature is of critical importance, especially in the developing world where livelihoods are inextricably linked to rainfed agriculture (Barker and Molle 2004). However, expected changes in precipitation and temperature remain uncertain in many regions. Time series of rainfall either observed (Manton et al. 2001; Frich et al. 2002; Dore 2005) or projected (Ruosteenoja et al. 2003) indicate that climate change may manifest itself through more complex and spatially variable impacts on precipitation than on temperature. Characterising future precipitation and temperature changes usually includes the simulation of these two variables' space-time variations using climate models, either global or regional, and the quantification of observed long-term changes. Many global climate models (GCM) were developed since the early 1990s, including ECHAM4 (Roeckner et al. 1996), HADCM3 (Johns et al. 2003), CSIRO-MK3 (Gordon et al. 2002), CGCM3.1 (Flato et al. 2000). Several studies related to climate change have been undertaken in Southeast Asia with different objectives: characterizing and quantifying climatic changes (Hoanh et al. 2003; Ruosteenoja et al. 2003; Snidvongs et al. 2003; Mac Sweeney et al. 2008), predicting future river discharge and lake water levels (Eastham et al. 2008; TKK and SEA START RC 2009), assessing vulnerability to climate change (Anshory-Yusuf and Francisco 2009), formulating recommendations for mitigation of- and adaptation to climate change (Eastham et al. 2008; Salim et al. 2009; TKK and SEA START RC 2009). A detailed review of these climate change studies is available in the Electronic Supplementary Material. Table 1 summarizes their results and indicates that projected changes in annual precipitation are either positive or negative depending on the models, the scenarios and the periods considered. In some cases, the direction of change remains uncertain. Changes in seasonal precipitation and temperature are more consistent: past analyses generally conclude that the wet season and the dry season will become wetter and drier respectively and that temperature will increase at rates ranging from +0.01 to +0.05°/year. Most of these reviewed studies compared mean values of climate variables averaged over successive 10- to 30-year periods, thus capturing the multi-decadal variability of the climate and explaining the diversity of the results. The coarse resolution and the inability of each climate model to accurately simulate actual climate dynamics also explain the discrepancies between climate variables projected by different models, especially precipitation whose variability is controlled locally. In contrast, the consistency of the different projected temperature changes, all showing a temperature rise, is due to the lower multi-annual natural variability of temperature, overwhelmed by the regional influence of global warming.

Table 1 Summary of projections of annual and seasonal precipitation and annual temperature in Southeast Asia from previous studies

Authors	Location	Models	Scenarios	Period	Annual Rain change	Change in seasonal rainfall pattern	Temperature change
Snidvongs et al. (2003)	Lower Mekong catchment	CCAM	Doubling of CO_2 concentration			Drier dry season. Longer, 1-month delayed wet season	From + 0.01 to +0.03°C/y
Ruosteenoja et al. (2003)	Southeast Asia	7 GCMs	A1F1, A2, B1, B2	1961-2095	Either >0 or <0, depend on models and scenarios. Almost always unsignificant		From +0.01 to +0.05°C/y
Hoanh et al. (2003)	Mekong catchment	HADCM3	A2, B2	1960-2099	1961-2039: from -3.24 to +2.06mm/y 1961-2099: from -4.28 to 3.83mm/y		1961-2039: +0.02°C/y 1961-2099: from 0.026 to 0.036°C/y
Mac Sweeney et al. (2008)	Cambodia (Ca), Vietnam (Vi)	15 GCMs	A2, A1B, B1	1970-2090	From +0.3 to +0.6mm/year	Wetter wet season (+0.8 to +1.5mm/y (Ca) and +0.4 to +1.5mm/y (Vi))and drier dry season(-0.7 to -0.1mm/y (Ca) and -0.3 to -0.1mm/y (Vi))	From +0.014 to +0.045°C/y
Eastham et al. (2008)	Lower Mekong catchment	11 GCMs	A1B	1976-2030	From +0.1 to 9.9mm/y	Wetter wet season (+1.7 to +6.1mm/y) and drier dry season (-0.3mm/y unsignificant)	From +0.012 to +0.014°C/y
Salim et al. (2009)	Thailand, Vietnam	MAGICC	A1F1, B2	1990-2100	1990-2050: -1.62 to +1.26mm/y (B2) and - 0.66 to -1.14mm/y (A1F1) ; 1990-2100: +3.27 to +4.91mm/y (A1F1) and -1.63 to -2.45mm/y (B2)		From +0.03 to +0.06°C/y

PRECIS (Providing Regional Climates for Impacts Studies) appears to have been one of the most frequently used regional climate models (RCM) in Southeast Asia over the last five years. It was developed by the Hadley Center (Jones et al. 2004) with a spatial resolution of 0.22°×0.22°, more appropriate for regional studies, compared to an order of magnitude coarser resolutions of GCMs. PRECIS has been used to generate climate projections in India (Kumar et al. 2006), Pakistan (Islam et al. 2009), China (Zhang et al. 2006), southern Africa (Tadross et al. 2005) and South America (Marengo et al. 2009). It has been downscaled for Southeast Asia (fig. 1) by the "Southeast Asia SysTem for Analysis, Research and Training" (SEA-START) Regional Center, using the atmospheric general circulation model ECHAM4 to force its lateral boundaries under the SRES emission scenarios A2 and B2 (Nakicenovic et al. 2000). Compared to observed data from 130 weather stations during the 1980s throughout Southeast Asia, precipitation and temperature output from PRECIS were found to be biased in some areas, with temperature overestimated by 1 to 2 degrees and annual precipitations underestimated by over 100mm (Vastila et al., 2010). Chinvanno (2009) adjusted the data, using correction coefficients, calculated from simulated and observed values at specific grid cells over the 1980s, and interpolated to the whole grid applying kriging techniques. Bias-corrected daily precipitation and temperature data were found to differ from observed data by less than 50mm/year and 1 degree/year, respectively.
Quantification of human-induced changes in precipitation and temperature first requires discriminating them from natural climate variability. It is generally accepted that natural variability alters the climate pattern on time scales shorter than 30 years (World Meteorological Organization, 1996). However, the analysis of multi-centennial time series of observed (Beran 1994) or proxy (Sano et al. 2009) hydro-climatic data reveals the existence of wet or dry periods exceeding 50 years, although there are no long term trends. This natural behavior, named long-term persistence or Hurst phenomenon was first identified by Hurst (1951). It was recently demonstrated that this phenomenon can be explained by the multi-scale variability of hydro-meteorological time series also called scaling effect (Koutsoyiannis, 2002). The scaling effect, which denotes the invariance properties of a time series aggregated on different time scales, can be formulated as follow: $\sigma_k=k^H\sigma$ where σ is the standard deviation of the original annual time series X_i (i=1, 2…), σ_k is the standard deviation of $Z_i^{(k)}$, $Z_i^{(k)}$ being an aggregated time series of X_i at the k-year time step (k=1, 2,…): $Z_1^{(k)}=X_1+\ldots+X_k$, $Z_i^{(k)}=X_{(i-1)k+1}+\ldots+X_{ik}$. H is the scaling coefficient, generally varying between 0.5 (no scaling effect) and 1. By assuming that data are independent and identically distributed, previous statistical analyses aimed at detecting unidirectional trends in climate time series have not accounted for this form of auto-correlation which inflates the variance of the test statistic and increases the chance of a significant answer, even in the absence of a trend (Cox and Stuart 1955). Recently, Hamed (2008) modified the Mann–Kendall test (Mann 1945; Kendall 1975) to account for the scaling effect, thus enhancing the ability of the test to discriminate multi-scale variability from unidirectional trends.

In this paper, the Mann-Kendall test modified by Hamed (2008) is applied to temperature and precipitation variables capturing the intensity, seasonality and extremes in precipitation and temperature over the period 1960-2049. These variables were derived from daily precipitation and temperature grid-based time series produced by the RCM PRECIS using boundary conditions from the ECHAM4 GCM under the SRES scenarios A2 and B2 in continental Southeast Asia.

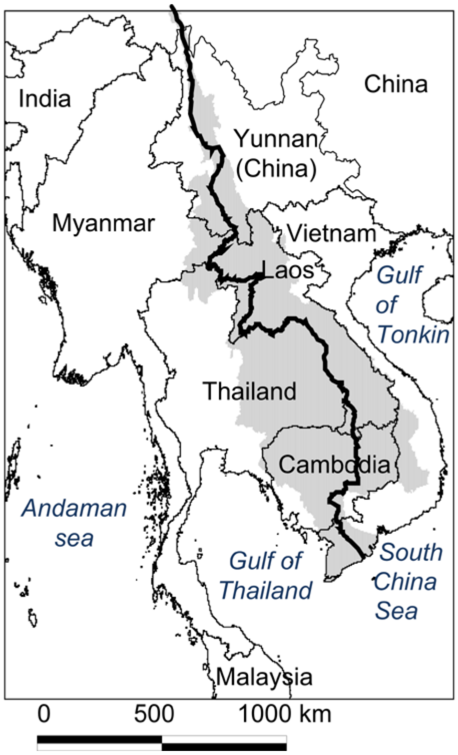

Fig. 1 Continental Southeast Asia and the Mekong River Basin (shaded area)

2. Methods

The domain of the PRECIS atmospheric and land surface regional climate model, forced by ECHAM4, extends from 90°E to 112°E and from 0°N to 35°N. In addition to bias-corrections performed by Chinvanno (2009), PRECIS rainfall and temperature data were tested to detect outliers. About 20 rainfall values exceeding 90,000mm/day and more than 300 values exceeding 2,200mm/days were identified among the 1.2 billion daily rainfall values of the model domain. Those outliers were found to have negligible effects on the study results, because of their relative scarcity and the low sensitivity of the Mann-Kendall test to outliers. No outliers were found in temperature values. Twenty four annual variables, capturing the intensity, seasonality and extremes in precipitation and temperature, were derived from the PRECIS grid-based daily precipitation and temperature time series and gathered in five categories:

- Occurrence of the wet season (variables 1 to 3): these 3 variables include the number of days since the 1st of January to the beginning / end of the wet season and to the first day of the wettest 5-day period. The beginning of the wet season was defined as the first day of the first 10-day period of the year that satisfies two conditions: i) the cumulative precipitation depth of this 10-day period exceeds the mean 10-day precipitation depth averaged over the period 1961-1990 and ii) at least two of the next three 10-day periods satisfy the first condition. Due to the extreme temporal variability of precipitation, the 10-day precipitation depths were first smoothed by a 3-time-step moving average. The end of the wet season was defined by symmetrical conditions, starting from the end of the calendar year and moving backward through the 10-day periods (fig. 2A).
- Cumulative precipitation depths per season and per range of daily precipitation (variables 4 to 15): these 12 variables correspond to the sums of daily precipitation for specific pairwise combinations of three periods (full year, wet and dry seasons) and four ranges of daily precipitation (whole range, low, medium and high precipitation). Low, medium and high

precipitation were defined by two thresholds determined as follows: for each of the four precipitation ranges, the sorted cumulative distribution of daily precipitation over the period 1961-1990 was split into three identical depths, thus defining two values corresponding to one third and two thirds of the total depth of this distribution. The daily precipitation thresholds were defined as the antecedents of these two values using the sorted cumulative distribution function (fig. 2B).

- Extreme events (variables 16 to 18): these variables are related to precipitation depth (cumulative depth of the wettest 5-day period), frequency (number of rainy days whose precipitation depth exceeds the 90^{th} heaviest daily precipitation of the period 1961-1990, i.e. there are 3 extreme events per year on average) and length (longest drought defined as the number of consecutive 'dry' days, with precipitation < 1mm/day, during the wet season. These events are particularly harmful for farmers who grow rainfed rice as it can drastically reduce crop yields).
- Precipitation intensity index (variable 19): this variable captures the combined effect of precipitation frequency and intensity, calculated as the number of heaviest rainy days that constitutes two thirds of the total annual precipitation as recommended by Sun et al. (2006).
- Temperature (variables 20 to 24): these variables include mean annual temperature, mean temperatures of the coldest and warmest 10-day periods and the numbers of days between the first of January and the first day of these 10-day periods.

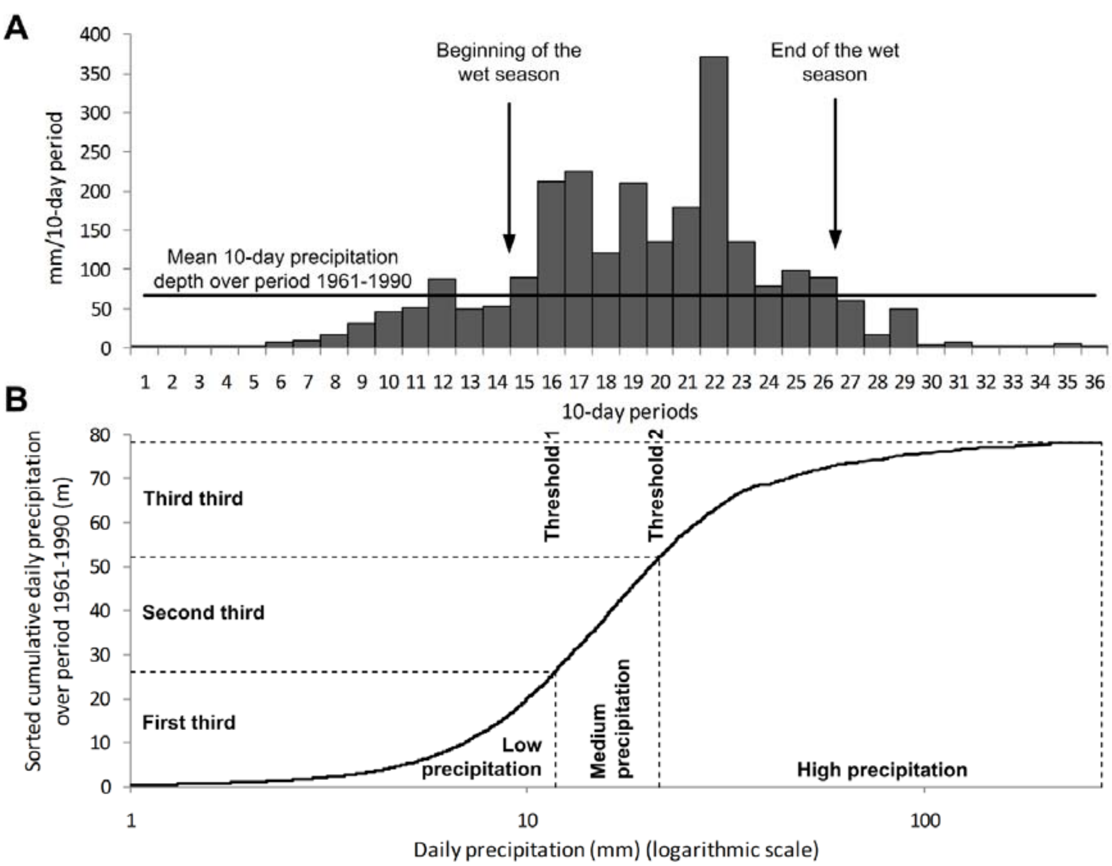

Fig. 2 Graphical illustration of methods used to generate the threshold values used in variables 4 to 15 (A) and to determine the occurrence of the beginning (variable 1) and end (variable 2) of wet season (B) at example grid cell

At each cell of the PRECIS grid, the 24 time series of the above variables were analyzed with the Mann-Kendall (Mann 1945; Kendall 1975) statistical test, recently modified by Hamed

(2008) to account for long-term persistence. The main steps of calculations are summarized below. Further details can be found in Hamed (2008). Given a time series X_i (i=1, …n), the test statistic S of the original Mann-Kendall test is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \text{ where } sgn(\theta) = \begin{cases} 1 \; if \; \theta > 0 \\ 0 \; if \; \theta = 0 \\ -1 \; if \; \theta < 0 \end{cases}$$

Under the assumption that the data are independent and identically distributed, the variance $V_0(S)$ of the test statistic S is calculated as follows:

$V_0(S) = n(n-1)(2n+5)/18 - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)/18$ where m is the number of tied ranks, each with t_i tied observations. The standardized variable Z, obtained from S and $V_0(S)$, is given by:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V_0(S)}} \; if \; S > 0 \\ 0 \qquad if \; S = 0 \\ \dfrac{S+1}{\sqrt{V_0(S)}} \; if \; S < 0 \end{cases}$$

The significance of trends is tested by comparing Z with the standard normal variate at the desired significance level α. In our analysis, we selected α=95%. Under the scaling hypothesis, the modified Mann-Kendall test proposed by Hamed (2008) includes three steps. Step 1: the original Mann-Kendall test is applied to the data. If Z is not significant, it can be concluded that the time series does not show any significant trend. If Z is significant, the effect of scaling is checked in step 2. Step 2: the original time series is detrended using the non parametric trend estimator proposed by Sen (1968). The equivalent Normal variates Z_t are obtained from the detrended data, using the transformation introduced by Hogg and Tanis (1988) where R_t is the rank of detrended observations, n is the number of observations, and $\Phi^{-1}()$ is the inverse standard Normal distribution function:

$$Z_t = \Phi^{-1}\left(\frac{R_t}{n+1}\right)$$

The scaling coefficient of the equivalent Normal variates is estimated by maximizing the log-likelihood function (logL()) proposed by MacLeod and Hipel (1978) where γ_0 is the variance of matrix Z_t and $C_n(H)$ is the correlation matrix for a given scaling coefficient H:

$$\log L(H) = -\frac{1}{2} log|C_n(H)| - \frac{Z_t^T [C_n(H)]^{-1} Z_t}{2\gamma_0}$$

The existence of the scaling effect ($H \neq 0.5$) is tested using the mean and standard deviation of H for the uncorrelated case, estimated by Hamed (2008). If there is no scaling effect, it is concluded that the time series shows a significant trend whose slope is estimated using the Sen's slope estimator (Sen 1968). If there is a scaling effect, the variance of the modified test statistic is calculated in step 3. Step 3: the modified variance $V(S)$ of the test statistic is derived from the work of Kendall and Stuart (1976) and given by:

$$V(S) = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sum_{k=1}^{n-1} \sum_{l=k+1}^{n} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho_{jl} - \rho_{il} - \rho_{jk} + \rho_{ik}}{\sqrt{(2-2\rho_{ij})(2-2\rho_{kl})}} \right)$$

where ρ_{ij} is the autocorrelation coefficient at lag i-j. The modified variance is finally corrected for bias with the factor B established by Hamed (2008) as a function of n and H. The modified test statistic Z^* is calculated using the unbiased modified variance:

$$Z^* = \begin{cases} \dfrac{S-1}{\sqrt{V(S)B}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{V(S)B}} & if\ S < 0 \end{cases}$$

If Z^* is not significant at the 95% desired significance level, it is concluded that the observed trend is not significant. If Z^* is significant, there is a significant trend whose slope is estimated using the Sen's slope estimator (Sen, 1968).

3. Results

The distribution of significant trends in precipitation and temperature over the period 1960-2049 is illustrated in figures 3 to 6, using color scales representing the values of the Sen's slope. Uncolored areas correspond to the absence of significant changes.

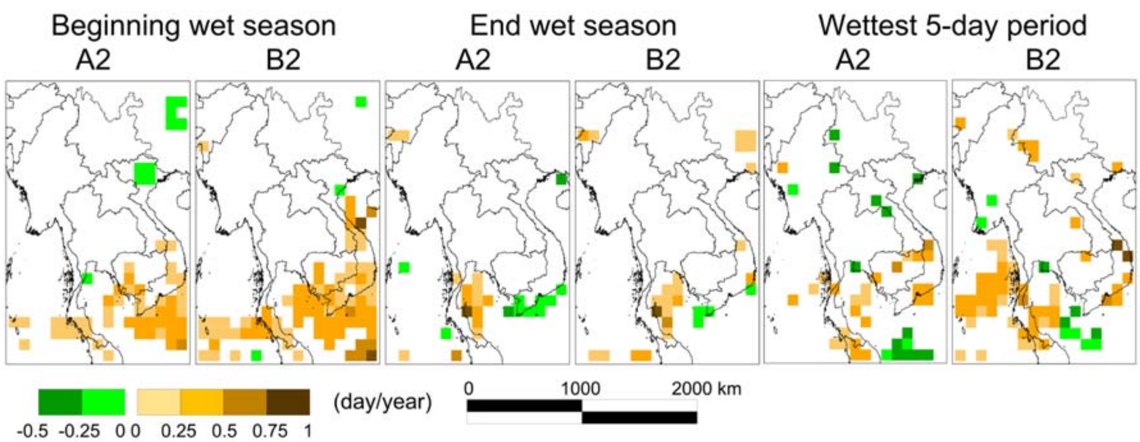

Fig. 3 Significant trends in the occurrence of the wet season (beginning, end and peak) (variables 1 to 3)

Figure 3 displays the spatial distribution of significant trends in the occurrence of the wet season and of its peak. Changes in the beginning of the rainy season are minor. In total, they affect between 15% (scenario A2) and 21% (scenario B2) of the study area's surface area, mainly in the Andaman and South China Seas. On average, the beginning of the wet season will be delayed by about 0.16 day/year (scenario A2) and 0.29 day/year (scenario B2) in these areas, while the end of the wet season remains mostly unchanged. Significant trends in the occurrence of the wettest 5-day period result in delays of about 0.32 day/year for both scenarios, over 18% and 16% of the study area's surface area for scenarios A2 and B2 respectively.

Figure 4 illustrates the distribution of significant trends in precipitation depths. Significant upward and downward trends in annual precipitation, considering the whole range of daily precipitation, cover 20% (Central and Northern Myanmar and the Gulf of Thailand) and 10% (South China, Andaman Sea and the Gulf of Tonkin) of the total study area's surface area, respectively. Increased precipitation mainly occurs during the wet season and affects high precipitation, while precipitation decreases occur during both dry and wet seasons and especially affect low precipitation. Areas subject to annual low precipitation decreases and to annual high precipitation increases represent about one half and one third of the study area's surface area respectively. Except for the Gulf of Thailand which receives higher precipitation, most of the precipitation increases are observed on land areas whereas precipitation decreases dominate over the sea. Mean rate of high precipitation increase during the wet season ranges from +2.7 mm/year to + 3.1 mm/year for scenarios B2 and A2 respectively. Mean rate of low precipitation decrease ranges from -1.4 mm/year to -1.3 mm/year for scenarios B2 and A2 respectively. On average, surface areas with increasing precipitation are similar in both scenarios (10% and 12% of the study area's surface area for scenarios B2 and A2 respectively). In contrast, areas with decreasing precipitation are narrower in scenario A2 (16% of surface area) than in scenario B2 (19% of surface area). Thus, scenario A2, which projects more greenhouse gas emissions than B2, is wetter than scenario B2.

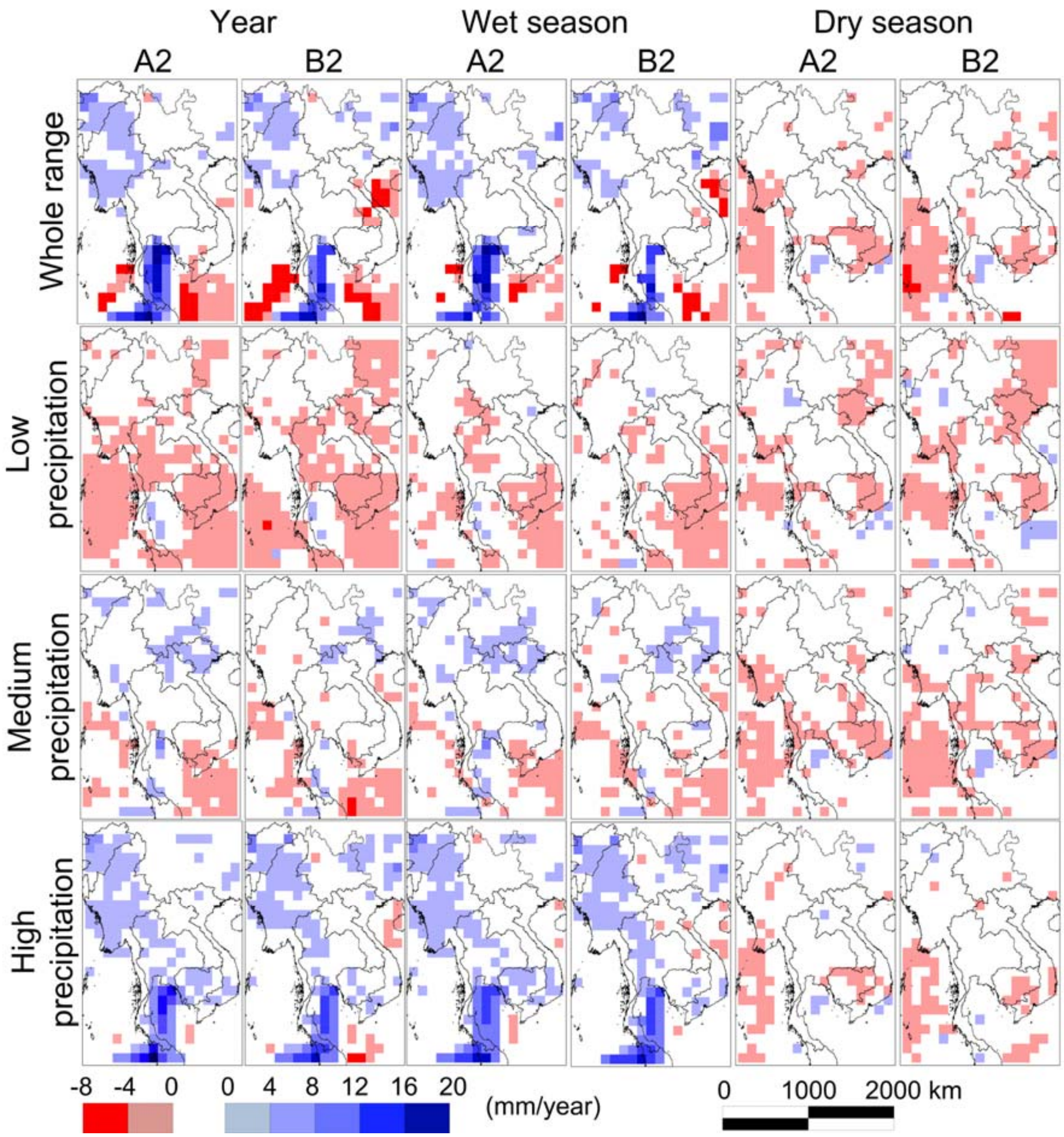

Fig. 4 Significant trends in annual cumulative precipitation depth per range of daily precipitation and per season (variables 4 to 15)

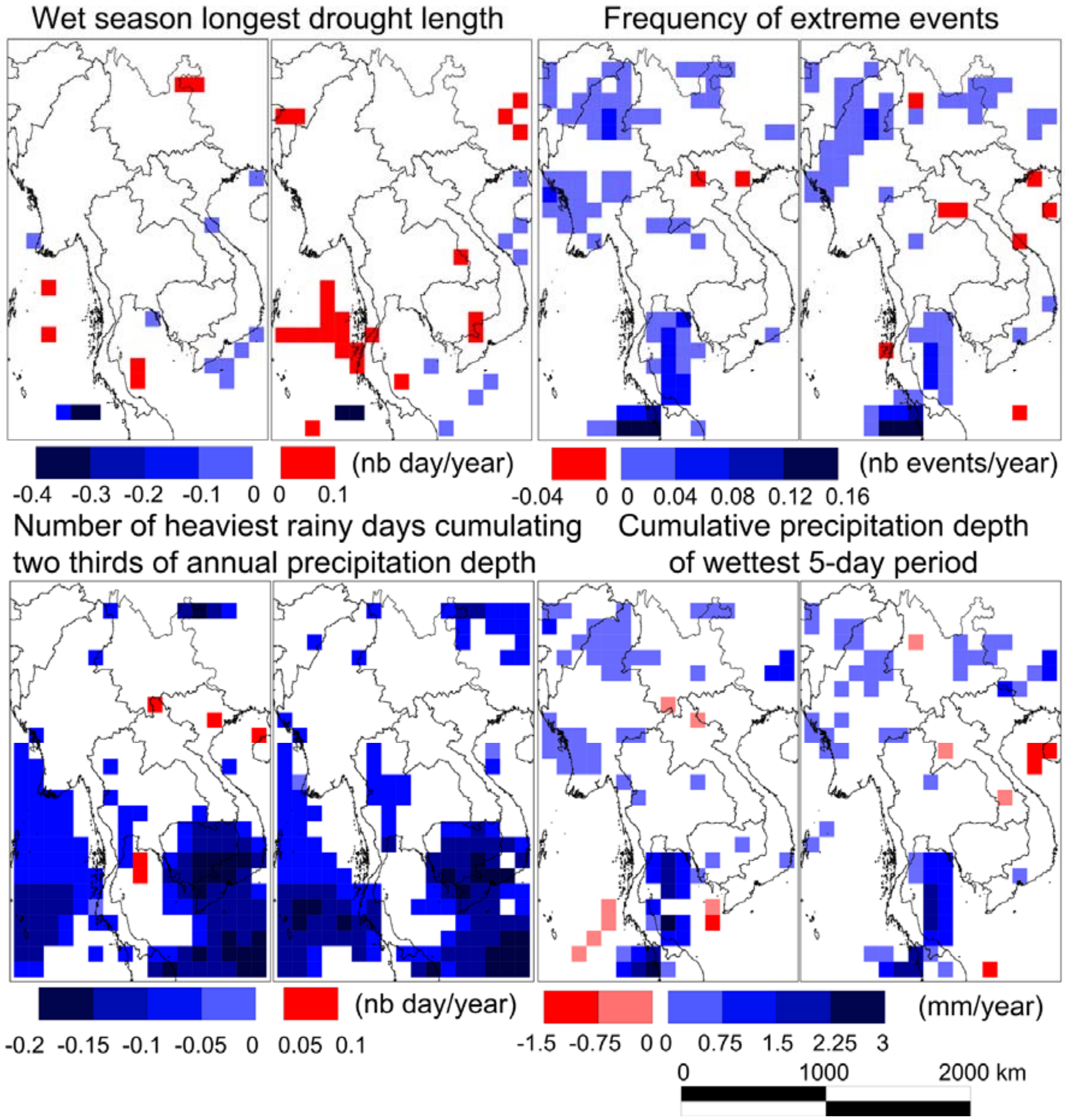

Fig. 5 Significant trends in extreme rainfall events (variables 16 to 19)

Figure 5 displays the spatial distribution of significant trends in extreme rainfall events. Significant trends in the length of the longest drought during the wet season affect less than 10% of the study area's surface area, mostly over the sea. The geographical pattern of changes in the frequency of extreme events is similar to that of change in high precipitation occurring during the wet season (cf. fig. 4). It consists mainly of increases covering about 10% of the study area's surface area, over the Gulf of Thailand and in Central and Northern Myanmar. Changes in the number of heaviest rainy days whose cumulative depth represents two thirds of total annual precipitation are mostly negative, meaning that the distribution of precipitation throughout the year will become more contrasted. According to figure 4, significant trends in this variable are mainly caused by a reduction of annual low precipitation rather than by an increase of high precipitation. These changes are concentrated in the Andaman Sea, in Cambodia, in Southern Vietnam and in the South China Sea, covering more than one third of the study area's surface area. Mean change rates are about -0.1 day/year. Changes in the cumulative precipitation depth of the wettest 5-day period are mostly positive, ranging from

0.61 mm/year (scenario B2) to 0.64 mm/year (scenario A2). Their spatial distribution is similar to that of changes in high precipitation (fig. 4) and in the frequency of extreme events.

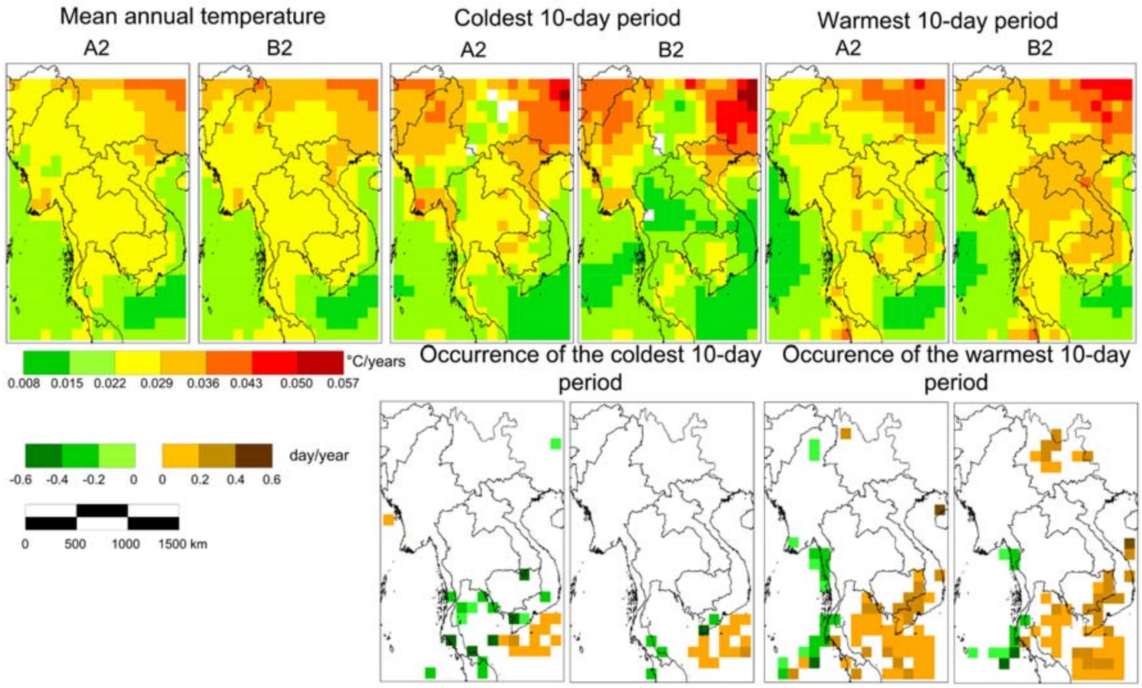

Fig. 6 Significant temperature trends (variables 20 to 24)

Figure 6 displays significant temperature trends. In contrast to precipitation change whose significance is restricted to a few areas, temperature trends are significant over more than 99% of the study area's surface area and all follow the global warming trend. The mean annual temperature increase over the study area ranges from 0.023 °C/year to 0.024 °C/year for scenarios A2 and B2 respectively. Scenario B2 induces the highest increase of temperature during the warmest 10-day period (scenario A2: 0.023 °C/year, scenario B2: 0.026 °C/year). Figures are in reverse order for average temperature increase during the "coldest 10-day period" (scenario A2: 0.024 °C/year, scenario B2: 0.022 °C/year). The highest rates of warming are localized in the northern part of the study area (China) and these rates diminish southward. Temperature increases are higher on the land than on the sea. Significant trends in the occurrence of the coldest and warmest 10-day periods are grouped in the southeast part of the region and quasi exclusively over the sea (gulf of Thailand and South China Sea). They cover 5%-8% and 17%-18% of the study area respectively. They predominantly consist in delays rather than ahead of time. Most areas showing significant delay in the occurrence of the warmest 10-day period are similar to that showing delay in the beginning of the wet season.

4. Discussion

This study attempted to quantify fine-scale changes in precipitation and temperature characteristics in continental Southeast Asia, applying the modified (Hamed, 2008) Mann-Kendall trend detection test to climate output from the RCM PRECIS. This modified test, accounting for natural long term persistence in climate data, reduces the risk of confusion between multi-decadal natural variability and long-term unidirectional trends. The attribution of the observed precipitation trends to global warming should be cautiously considered as precipitation changes depend in part on spatial patterns of temporally varying sea surface temperature. Therefore, it cannot be excluded that global warming results in non-unidirectional changes in precipitation. Reversely, long-term unidirectional trends could theoretically reflect a natural cycle un-related to global warming. However, natural cycles exceeding 90 years are unlikely to exist in ECHAM4 simulated time series and downscaled PRECIS output data (Koutsoyiannis et al. 2008), thus strengthening the causal effect between the SRES emission scenarios and the long term unidirectional trends detected in the present study.

Our analyses indicate that, except for annual low precipitation whose significant trends cover nearly half of the region's surface area, all other precipitation variables show significant trends over less than one third of the study area's surface area. In contrast, temperature significantly increases over more than 99% of the surface area. Decreasing precipitation trends are generally found in areas where temperature rises at lower rates, mainly over the sea, whereas regions becoming wetter correspond to areas with high temperature rises, in land areas. This illustrates the land-sea contrast typical of the monsoon climate (Webster et al. 1998). Higher temperature over lands induces higher evapotranspiration rates, thus increasing air humidity and precipitation (Trenberth 2005). These warmer conditions could also increase the strength of the thermal low, thereby inducing more moisture inflow from the ocean, contributing to the precipitation increase. Such causal links between temperature rise and precipitation increase was recently evidenced at the global scale (Previdi and Liepert 2008).

For each climate variable, the total number of significant trends was compared to that obtained from the original Mann-Kendall test. Trends found significant and insignificant by the original and the modified test, respectively, are attributed to the scaling effect only. According to the original Mann-Kendall test, about 10% of significant trends in the frequency of extreme events and in the occurrence of the wettest 5-day period, and about 16% of significant trends in the length of the longest wet season drought were found to be caused by the scaling effect only. This ratio rises up to 33% and 65% for the variables corresponding to the beginning and the end of the rainy season, respectively. Therefore, for these two variables, in average, about half of the significant trends detected by the original Mann-Kendall test are likely to be caused by multi-year cycles occurring during the study period rather than by a long term and unidirectional climatic change. Although the cyclic phenomenon ENSO seems i/ to be captured by ECHAM4 (Cherchi and Navarra, 2003), and ii/ to control the length of the summer monsoon (Zhou and Chan 2007; Goswami and Xavier Y, 2002), no evidences explain why the occurrence of the wet season, in particular, is subject to the scaling effect. For other variables, less than 6% of significant trends estimated by the original Mann-Kendall test were found to be caused by the scaling effect.

Although it is not possible to accurately compare our results with those from previous analyses (cf. Table 1 and Electronic Supplementary Material) because of the differences in SRES scenarios and time periods specific to each analysis, some consistencies are worth mentioning. The annual precipitation increases in Vietnam and Cambodia estimated by Mac Sweeney et al. (2008) are extremely low (from 0.3 to 0.6 mm/year) and would probably have been considered insignificant, in agreement with this study's findings, if the authors had applied a statistical test to assess precipitation changes. In order to compare our results with those from Ruosteenoja et al. (2003) who worked at the sub-continental regional scale, the modified Mann-Kendall test was applied to annual precipitation time series averaged over the whole study area. Consistently, no significant change was observed for scenarios A2 and B2. Trends in seasonal precipitation, indicating wetter wet seasons and drier dry seasons (Snidvongs et al. 2003; Eastham et al. 2008; Mac Sweeney et al. 2008) are also consistent with the present findings, although the spatial extent of such changes are much more limited in the present study, especially over land areas.

All reviewed studies concluded that annual temperature will increase in Southeast Asia with a mean rate ranging from +0.018 ±0.008°C/year to 0.037 ±0.015°C/year. This range encompasses that from the current analysis (0.023 to 0.024 °C/year). The wider range obtained by previous studies originates from the use of more extreme scenarios (B1 and A1F1) over periods extending beyond 2050, including higher rates of temperature rise (IPCC 2007).

Possible implications of observed trends on agriculture can be inferred from seasonal precipitation and temperature trends displayed in figures 4 and 6. Total precipitation depth of the wet season does not show any significant trends in Thailand, Vietnam, Cambodia, Laos and Yunnan province of China. Most of the changes are located in central and northern Myanmar and result in precipitation increase. This should be beneficial for agriculture as this region is the driest (mean wet season precipitation in central/northern Myanmar and at the regional scale are equal to 670 mm/year and 1460 mm/year respectively over the period 1961-1990 according to PRECIS). Changes in dry season precipitation are concentrated in Cambodia and Southern Vietnam and result in precipitation decrease with minor consequences on food production as cropping periods are concentrated during the wet season. Higher temperatures observed over the whole region should slightly increase evapotranspiration, increasing water demand of crops and pastures in both rain-fed and irrigated systems. This may lead to enhanced biomass production as water is not a limiting factor during the wet season. In contrast, temperature increase can reduce crop yields by preventing pollination and inducing dehydration and floret sterility (Matsui and Omasa 2002; Peng et al. 2004). This could be offset by promoting the adoption of high temperature-tolerant cultivars. In mountainous areas where cold temperatures limit agricultural production (Northern Myanmar, northern Thailand, Northern Laos and Yunnan), rising temperature will favor agricultural production by extending the cropping period.

5. Conclusions

Most previous climate change analyses based on the PRECIS model downscaled for Southeast Asia either compared its mean climate output variables averaged over successive multi-year periods, or used the model's output as input to run hydrological models. Projected changes in intensity, seasonal distribution and extremes in precipitation and temperature remained unknown. By attempting to discriminate natural long-term persistence from long-term unidirectional trends, possibly associated to human-induced climate change, this study suggests that, except for central and northern Myanmar that will become wetter, precipitation will remain stable in most of the region's land areas. This study challenges most of the past analyses which generally captured and quantified the multi-decadal natural precipitation variability to conclude that climate is changing. Moreover, it questions the validity of the results obtained with similar methods in other parts of the world. In contrast, temperature will indeed follow the global warming trend over the entire study area. At the regional scale, precipitation and temperature changes should benefit agricultural production as significant precipitation increase will occur in the drier areas whereas steepest temperature rises will affect the coldest parts. Further analyses should focus on how these climate trends will interact with other environmental changes caused by the demographic and economic development occurring in the region.

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Electronic Supplementary Material

1. Review of previous climate change studies in continental Southeast Asia

Snidvongs et al. (2003) evaluated how the climate in the Mekong Basin may change if CO_2 concentration doubles from current levels to 700 ppm. According to SRES scenarios, this level should be reached between 2070 (scenario A1F1) and 2120 (scenario B2). Output from the Conformal Cubic Atmospheric RCM (McGregor 2005) was used to produce two simulation sets. In the first set, the space and time scales were respectively set to 80 km, and one year for each scenario. Simulations of the second set were run with a spatial resolution of 0.1° and covered a 10-year period. Changes in monthly precipitation and temperature were quantified for the entire Mekong Basin and five major landforms. Climate changes between the two CO_2 scenarios were likened either to the change in the monthly mean (first set) or to the change in the median annual value (second set). Both simulation sets concluded that, throughout Southeast Asia, the dry season will become drier and longer and the wet season will start one month later. The Thai Malay peninsula (fig. 1) will become drier during the wet season while the Gulf of Thailand and the Andaman Sea will receive more rain. At the Mekong basin scale, temperature will increase by 1-3^{o} C.

Ruosteenoja et al. (2003) used 7 coupled atmosphere-ocean GCMs to calculate changes in seasonal temperature and precipitation between a baseline period (1961-1990) and three 30-year periods centered around 2025, 2055 and 2085 in 32 sub-continental regions, including Southeast Asia. Simulations were mainly conducted for scenarios A2 and B2. Anthropogenic changes were distinguished from natural variability, using the statistical properties of climate variability inferred from two 1000-year simulations in which the composition of the atmosphere and other external forcing agents were kept constant. In Southeast Asia, all models indicate that temperature significantly increases by about 0.5-1.0°C, 1.0-3.0°C and 1.0-5.0°C between the baseline period and the periods centered around 2025, 2055 and 2085 respectively. Precipitation changes between the baseline and the 2025-centered and 2055-centered periods rarely exceed 10% and are either positive or negative depending on models and scenarios. Most of precipitation changes fall into the range of variations caused by natural variability. Changes from the baseline to the 2085-centered period are mainly positive, ranging from -5% to +20%.

Hoanh et al. (2003) used the HADCM3 GCM under A2 and B2 SRES scenarios to compare temperature and precipitation projections for the periods 2010-39 and 2070-99 with the baseline 1961-90 in the Mekong Basin. Monthly data sets were adjusted to observed data using the Climate Research Unit (CRU) grid (New et al 2000; Mitchell and Jones 2005) time series over the baseline. The authors found that mean temperature in the whole basin will increase by 1.0°C between the baseline and 2010-39 for both scenarios and by 4°C and 2.9°C between the baseline and 2070-99 for scenarios A2 and B2 respectively. For both scenarios, relative changes in annual precipitation between the baseline and 2010-39 varies between -6% and +6%, depending on the sub-basins. This range widens to (-12%; +32%) for the period 2070-99.

Mac Sweeney et al. (2008) generated 52 country-focused reports using actual climate data and 15 GCMs from IPCC (2007). Each country report details climate projections over the period 1960-2100, based on 2.5°×2.5° grid-based temperature and precipitation time series under A2, A1B and B1 SRES scenarios. Mean values of precipitation and temperature were averaged over successive 10-year periods. This study focuses on Cambodia and Vietnam in Southeast Asia. In both countries, temperature is expected to increase from 0.7 to 2.7°C by the 2060s, and from 1.4 to 4.3°C by the 2090s. Precipitation increases mainly because of a wetter wet seasons (-11% to +31% and -1% to +33% of precipitation by 2090s in Cambodia and Vietnam respectively), partially offset by drier dry seasons (-54% to +35% and -62% to +23%

of precipitation by 2090s in Cambodia and Vietnam respectively). The proportion of total rain that falls in high intensity events is projected, by all models, to increase by up to 14% in the 2090s.

Eastham et al. (2008) investigated the likely changes of the climate in the Mekong Basin by 2030. They quantified the uncertainty around future climate projections using 11 GCMs from IPCC (2007), selected by statistically comparing their output data with interpolated meteorological observation from the CRU grid. Regional temperature and precipitation time series were constructed from simulations under A1B scenario, using the pattern scaling approach (Santer et al. 1990), and used as input to run a monthly lumped water accounting model. The authors found that the mean annual Mekong flow is likely to increase by 21% in 2030.

TKK and SEA START RC (2009) analyzed the hydrological impacts of climate change in the Tonle Sap basin and the Mekong Delta. The RCM PRECIS forced by the GCM ECHAM4 was used as input to i/ the basin-wide hydrological "Variable Infiltration Capacity" (VIC) model to simulate future river runoff, and ii/ the Princeton Ocean Model (POM) to simulate future sea level change at the mouth of the Mekong River. Output from VIC, POM and PRECIS were used as input for the EIA 3D model simulating the hydrological behavior of the Mekong River floodplain system. Simulations were run for a baseline period (1995-2004) and four decades (2010s, 2020s, 2030s and 2040s). The results indicate that the Mekong River discharge will increase (decrease) in the wet (dry) season by about 5.14% (2.18%), equivalent to an annual 4.3% increase between the baseline and the period 2010-2049.

Anshory-Yusuf and Francisco (2009) mapped the vulnerability of various parts of Southeast Asia to climate change. This assessment was carried out by overlaying maps of i/ climate hazards (tropical cyclones, floods, landslides, droughts and sea level rise), ii/ population density, iii/ biodiversity and iv/ socio-economic factors. An overall climate change vulnerability map was obtained by integrating the above-mentioned criteria. The authors found that the most vulnerable parts of Southeast Asia include the Mekong River Delta, about 90% of the Cambodia's surface area and the Northern and Eastern parts of Lao PDR.

Salim et al. (2009) used the MAGICC GCM (Wigley and Raper 1997) combined with a macro-economic model and an energy systems model to assess future climatic changes and their impact in Southeast Asia. The study considered 3 timelines (2020, 2050 and 2100) under A1F1 and B2 scenarios and 3 emission cases: the reference situation (no policy option to reduce greenhouse gases as in SRES emissions scenarios) and the stabilization of greenhouse gases concentration at either 550 ppm (S550) or 450 ppm (S450). Results are provided for Indonesia, Philippine, Thailand and Vietnam. From 1990 to 2100, the increase in projected temperature, in the reference situation, ranges from 2.4°C (scenario B2) to 5.0°C (scenarios A1F1). Temperature increases are more moderate, ranging from 1.85°C (B2) to 2.36°C (A1F1) for S550 and from 1.36°C (B2) to 1.82°C (A1F1) for S450. In Thailand and Vietnam, results show decreases in precipitation over the period 1990-2050 for the reference emissions case: from -0.27 mm/day (B2) to -0.11 mm/day (A1F1). From 1990 to 2100, precipitation either increases or decreases, from -0.50 mm/day (B2) to +1.5 mm/day (A1F1). Under S550 and S450, changes are either more moderate (1990-2050 under B2), stronger (1990-2100 under B2), or even reversed (1990-2100 under A1F1). Considering the heterogeneity of these results, the authors conclude that projecting precipitation is more challenging than temperature.

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