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# Extreme climate projections over the transboundary Koshi River Basin using a high resolution regional climate model

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**Abstract**

The high-resolution climate model Providing REgional Climates for Impacts Studies (PRECIS) was used to project the changes in future extreme precipitation and temperature over the Koshi River Basin for use in impact assessments. Three outputs of the Quantifying Uncertainties in Model Prediction (QUMP) simulations using the Hadley Centre Couple Model (HadCM3) based on the IPCC SRES A1B emission scenario were used to project the future climate. The projections were analysed for three time slices, 2011−2040 (near future), 2041−2070 (mid-century), and 2071−2098 (distant future). The results show an increase in the future frequency and intensity of climate extremes events such as dry days, consecutive dry days, and very wet days (95th percentile), with greater increases over the southern plains than in the mountainous area to the north. A significant decrease in moderate rainfall days (75th percentile) is projected over the middle (high) mountain and trans-Himalaya areas. Increases are projected in both the extreme maximum and extreme minimum temperature, with a slightly higher rate in minimum temperature. The number of warm days is projected to increase throughout the basin, with more rapid rates in the trans-Himalayan and middle mountain areas than in the plains. Warm nights are also projected to increase, especially in the southern plains. A decrease is projected in cold days and cold nights indicating overall warming throughout the basin.

*Keywords:* Climate change; Climate projection; Koshi basin; PRECIS; Extreme climate

## 1. Introduction

The Himalayan mountains are a repository of water resources and biodiversity. The large population of this region relies heavily on monsoon rainfall and streamflow for agricultural production, hydropower generation, and other livelihood activities. These mountains are also very sensitive to climate change (Immerzeel et al., 2010; Shrestha and Aryal, 2011), which has serious implications for the environment and natural resources. Regional climate change due to global warming is associated with changes in hydrological behaviours such as precipitation pattern, intensity, and extremes (Hu et al., 2013). Such changes could have a profound impact on sectors such as agriculture, water, and disaster risk management in the Himalayan region.

In recent decades, the issue of climate change has become more prominent in the Himalayan region (Eriksson et al., 2009) and research on climate change has made some progress. Some studies have been made of climate change scenarios at sub-continental or national levels (Kulkarni et al., 2013; Kumar et al., 2011; Rupa Kumar et al., 2006; Syed et al., 2014), mainly focussed on changes in the mean of climate variables over time and space. However, one of the

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major concerns of global climate change is the potential for an increase in extreme events (Easterling et al., 2000). Many disasters in the region are associated with extreme rainfall events (Cho et al., 2016; Panday et al., 2014), while extreme temperatures can also lead to human casualties. Thus understanding the potential trends and variability in future climate extremes is of great important for the planning and management of natural resources as well as for disaster risk reduction. Although some studies have been carried out on climate extremes in the Himalayan region based on observed data (Baidya et al., 2008; Hingane et al., 1985; Islam, 2009; Shrestha et al., 2016), there have been very few studies of future projections (Agarwal et al., 2014, 2016). Since any change in the frequency and intensity of extreme climate events is likely to have an immediate impact on the natural environment, societal infrastructure, and people, estimation of such change has become essential for climate change impact assessment.

General circulation models (GCMs) provide scenarios of future climate projections and aspects of climate variability and extremes which can be instrumental for impact studies and adaptation planning. Future climate simulations are performed for different IPCC emission scenarios (IPCC, 2001); the result of these models indicate that future rainfall and temperature are likely to change but that the magnitude of these changes will be different in areas with different climatic regimes (IPCC, 2007). The outputs provided by GCMs have a coarse resolution which is insufficient for use by national policy-makers and planners; they need to be downscaled to a finer resolution at regional scale by applying appropriate downscaling techniques. In addition, the spatial distribution of precipitation varies significantly across the Himalayan region (Chalise, 1994; Ichiyanagi et al., 2007; Nepal, 2012; Shrestha, 2000; Subrahmanyam and Upadhyay, 1982). The hydrological regime of the region is also quite different from east to west (Immerzeel et al., 2009). The eastern river basins are heavily influenced by the summer monsoon, whereas the western river basins rely heavily on glacier melt and the melt of snow deposited during the winter season (Eriksson et al., 2009; Immerzeel et al., 2010; Lutz et al., 2014). It has also been suggested that the impact of climate change on the flow regime will be different in different river basins (Nepal and Shrestha, 2015). Particularly in the water sector, assessment of impact at river basin level has been found to be useful (Lutz et al., 2014; Rajbhandari et al., 2014), hence climate scenarios need to be developed for specific basins looking at specific sectors.

The transboundary Koshi River Basin, shared among China, Nepal, and India, has a high potential for water infrastructure development (Chinnasamy et al., 2015). However, the basin is also prone to a range of water-induced hazards, such as floods, flash floods, landslides, and erosion due to the steep topography,

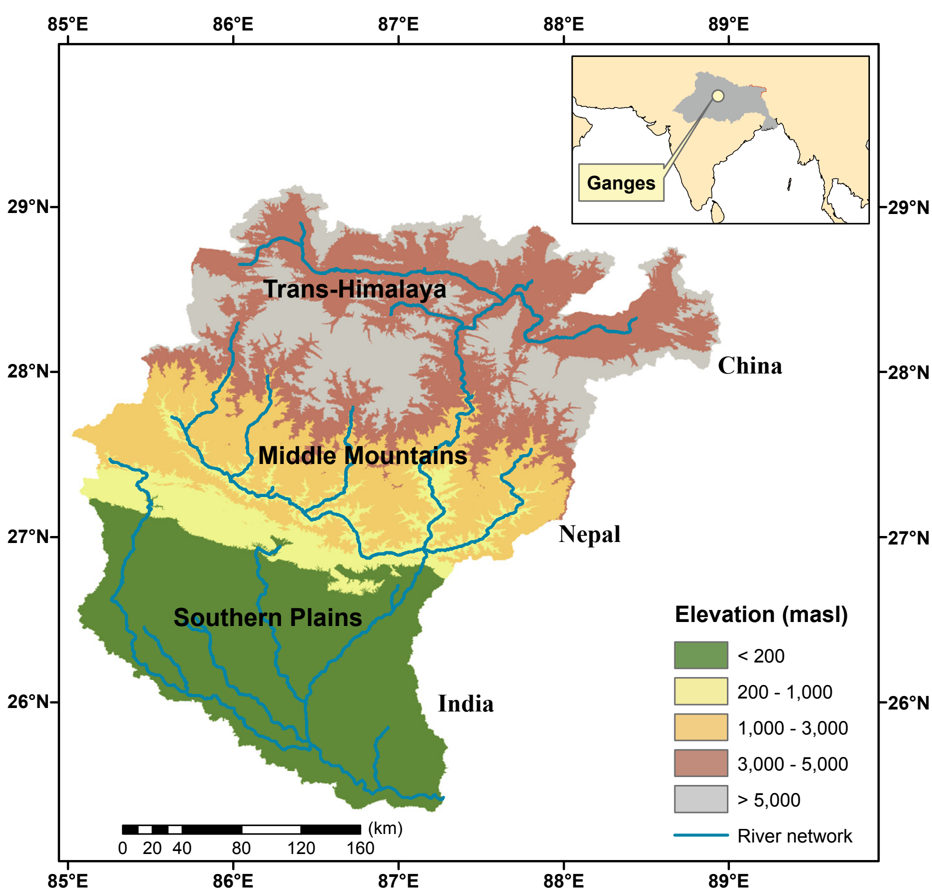


Fig. 1. The Koshi River Basin: location, major physiographic zones, and major rivers.

monsoon-dominated rainfall pattern, and young geological formation (Bharati et al., 2014; Chen et al., 2013; Nepal, 2012; Sinha et al., 2008). Studies have suggested that climatic and hydrological extreme events can have a negative impact on water resource development and can cause natural hazards (IPCC, 2012; Pathak et al., 2010; Shrestha, 2008). A good understanding of the spatial and temporal distribution of possible changes in extreme events is important for proper water resources and hazard planning and management.

The present study used a high-resolution climate model to project the changes in extreme precipitation and temperature over the Koshi River Basin. The projections show changes in the spatial distribution of extreme climate events at different future time slices with respect to the baseline period 1961—1990.

## 2. Data and methods

### 2.1. Study area

The Koshi River Basin lies in 25°18′ —29°09′ N, 85°01′—88°57′ E (Fig. 1). The basin covers an area of approximately 88,000 km$^2$: 45% in Nepal, 32% in China, and 23% in India. The elevation varies from just over 30 m above sea level (masl) in the

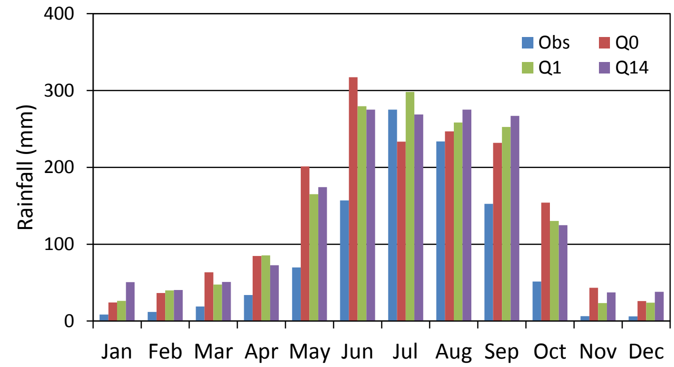


Fig. 3. Monthly area averaged precipitation over Koshi Basin (1961—1990).

plains to the south to more than 8000 masl in the high Himalayas and the wide range of climate—tropical climate in the south, warm temperate to cool temperate in the middle and alpine in the Himalayan peaks to the north—is observed (Dixit et al., 2009; Karki et al., 2015). More than 75% of the annual total precipitation is received during the monsoon season (Rajbhandari et al., 2016; Shrestha, 2000); the amount increases from the southern plains to the central middle mountains and valleys, and then decreases sharply in the trans-Himalayan region. In general, the

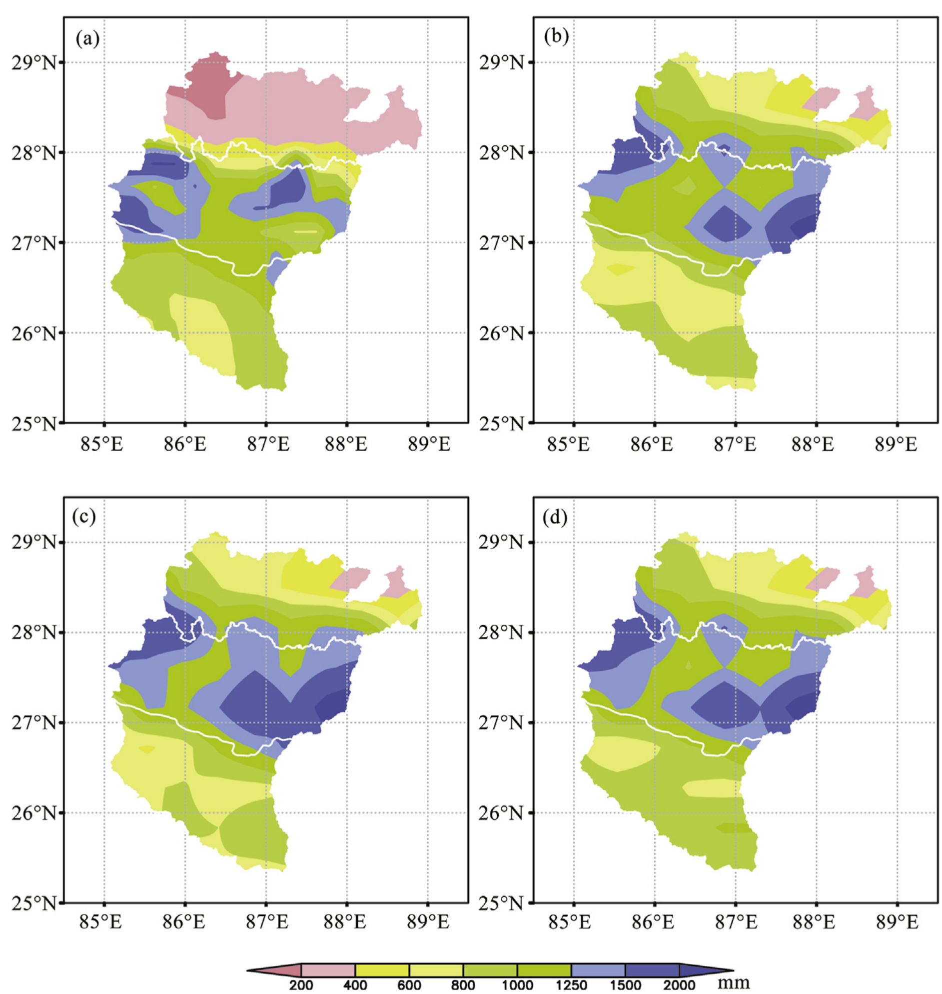


Fig. 2. Spatial distribution of summer (June—September) precipitation (mm) for the base period 1961—1990: (a) APHRODITE; (b) PRECIS Q0 simulation; (c) PRECIS Q1 simulation; (d) PRECIS Q14 simulation.

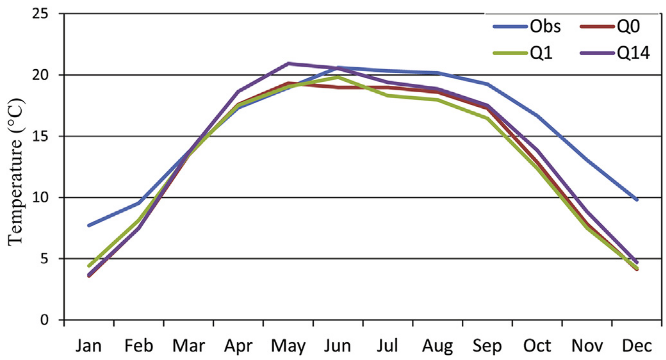


Fig. 4. Monthly distribution of area averaged temperature over the Koshi Basin (1961–1990).

temperature decreases from south to north. The basin is particularly prone to sedimentation, glacier melt, and a range of natural hazards including glacial lake outburst floods (GLOFs) (Chen et al., 2013; Nepal, 2012; Shrestha et al., 2010). It is thought that these hazards may increase in magnitude and frequency with climate change (Eriksson et al., 2009; Goswami et al., 2006). Although the basin can be divided into six distinct physiographic regimes based on elevation (Shrestha and Aryal, 2011), for the current study it was divided into three zones (Fig. 1): the trans-Himalaya to the north (essentially the region of the Tibetan Plateau), the middle mountains (which includes the valleys, hills, and high Himalaya mountains in the central part of the basin in Nepal, with an elevation from 200 to more than 5000 masl), and the southern plains (below 200 masl, in Nepal and India).

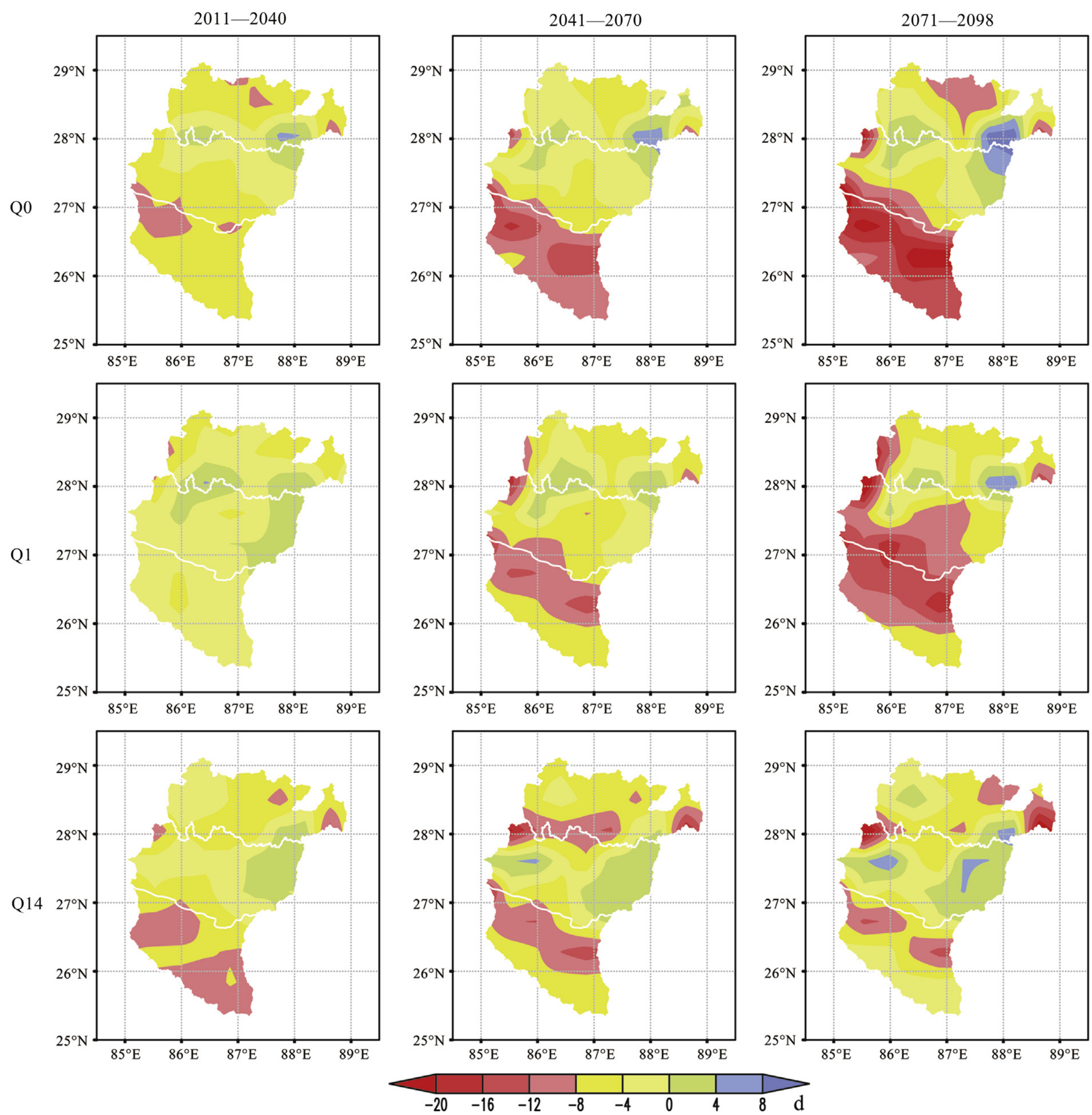


Fig. 5. Projected change in number of rainy days from the base period (1961–1990) as simulated by PRECIS.

### 2.2. The PRECIS model

There are considerable differences among the projections in precipitation and temperature derived from different GCMs. The complex topography of the Himalayan region makes it difficult for climate models to simulate past climate over the region, especially rainfall (Kripalani et al., 2007; Turner and Annamalai, 2012). And future projections of rainfall show considerable inter-model variability (Annamalai et al., 2007). The aim is to choose the model which performs best over the region.

The spatial pattern of the Indian summer monsoon is captured well by a few GCMs (Kripalani et al., 2007), especially the HadCM3 model developed by the Hadley Centre, UK, which has been shown to simulate the inter-annual summer monsoon mean and variability well (Kamala, 2008). The lateral boundary conditions (LBC) of three simulations (Q0, Q1, and Q14) generated using the Hadley Centre Coupled Model version 3.0 (HadCM3) under the Quantifying Uncertainties in Model Prediction (QUMP) project were provided by the Hadley Centre to the Indian Institute of Tropical Meteorology (IITM, Pune). They were chosen because of their ability to simulate the gross features of the Indian summer monsoon. PRECIS generated high-resolution (50 km × 50 km) climate change scenarios were prepared using the LBCs of Q0, Q1, and Q14 simulations for the SRES A1B scenario and provided to ICIMOD by IITM. The selection of the domain size for the three QUMP simulations is discussed in Rupa Kumar et al. (2006) and Kumar et al. (2011). PRECIS has been shown to be relatively successful in representing the climate of the Himalayan region (Akhtar et al., 2008; Kumar et al., 2011; Nepal 2016; Rupa Kumar et al., 2006; Syed et al., 2014). The three simulations were configured to 1.5°–38°N, 56°–103°E. The

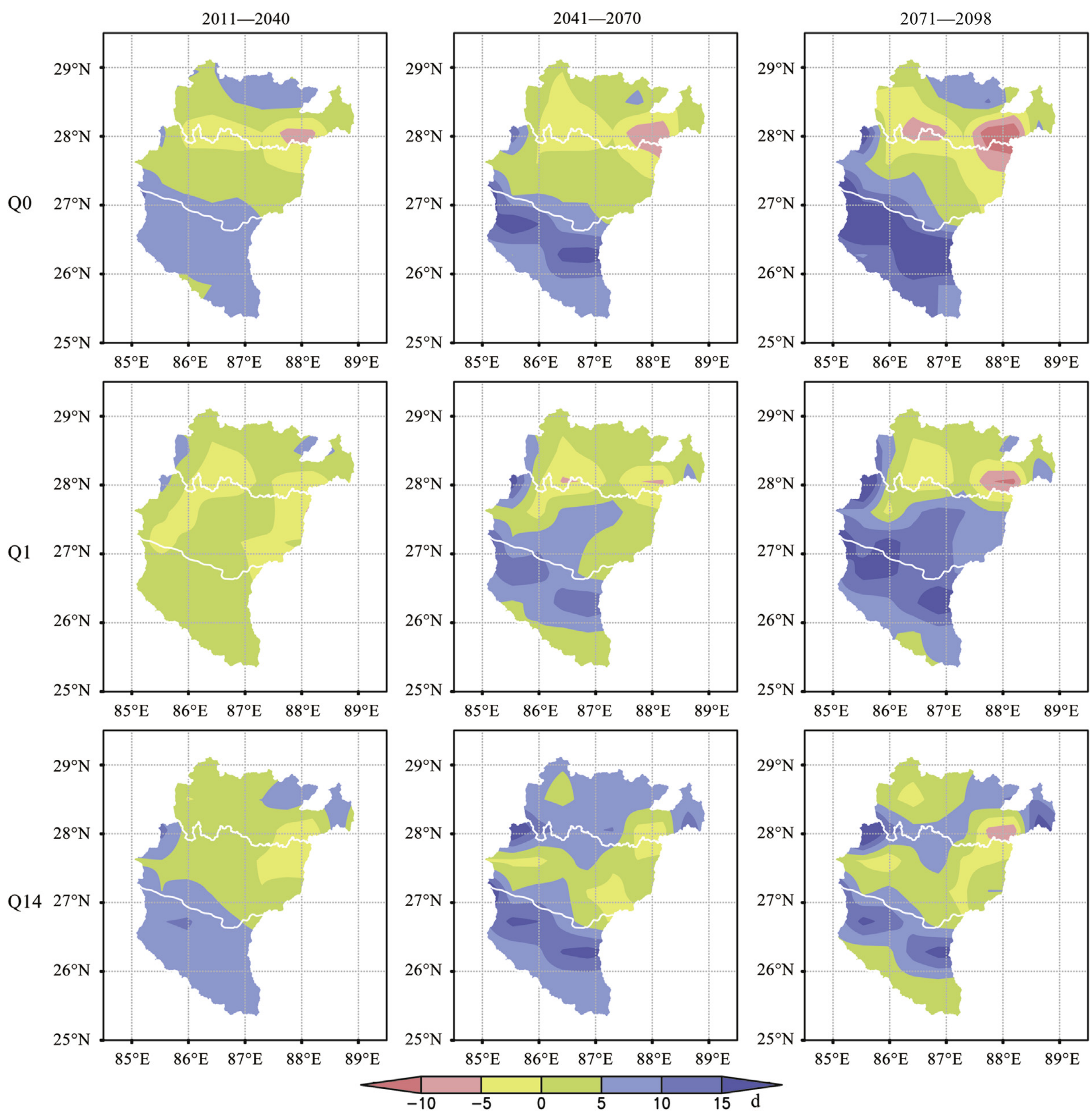


Fig. 6. Projected changes in consecutive dry days from the base period (1961–1990) as simulated by PRECIS.

continuous 138 years of output have been validated for their skill in simulating the present climate over India (Patwardhan, 2013), and have been used to project the future climate over India (Kumar et al., 2011), the Himalayan region (Kulkarni et al., 2013), and the Indus basin (Rajbhandari et al., 2014).

### 2.3. Observed data

APHRODITE's Water Resources (Asian Precipitation−Highly−Resolved Observational Daily Integration Towards Evaluation of Water Resources; www.chikyu.ac.jp/precip/) gridded data, which are based on rain gauge observations, were used to evaluate the baseline rainfall simulation (Yatagai et al., 2009, 2012). We used the 0.25° resolution data from the APHRO_V1101 version, which includes more rain gauge data than the previous version (Yatagai et al., 2012). These gridded datasets are publicly available for 1951−2007 and are considered to be a reliable precipitation product for the Himalayan region (Agarwal et al. 2014; Duncan and Biggs, 2012).

For the evaluation of extreme temperature distribution, we used APHRODITE's Water Resources 0.25° longitude and latitude resolution daily mean temperature data (Yasutomi et al., 2011), which are available for the monsoon Asia domain for 1961−2007, and maximum and minimum temperature data from Princeton University Hydroclimatology Group Bias Corrected Meteorological Forcing Datasets (Sheffield et al., 2006), which are available globally for 1947−2007 at 1.0° × 1.0° resolution. As the Princeton data is coarse resolution, we used the diurnal temperature range from this dataset and applied it to APHRODITE's mean daily

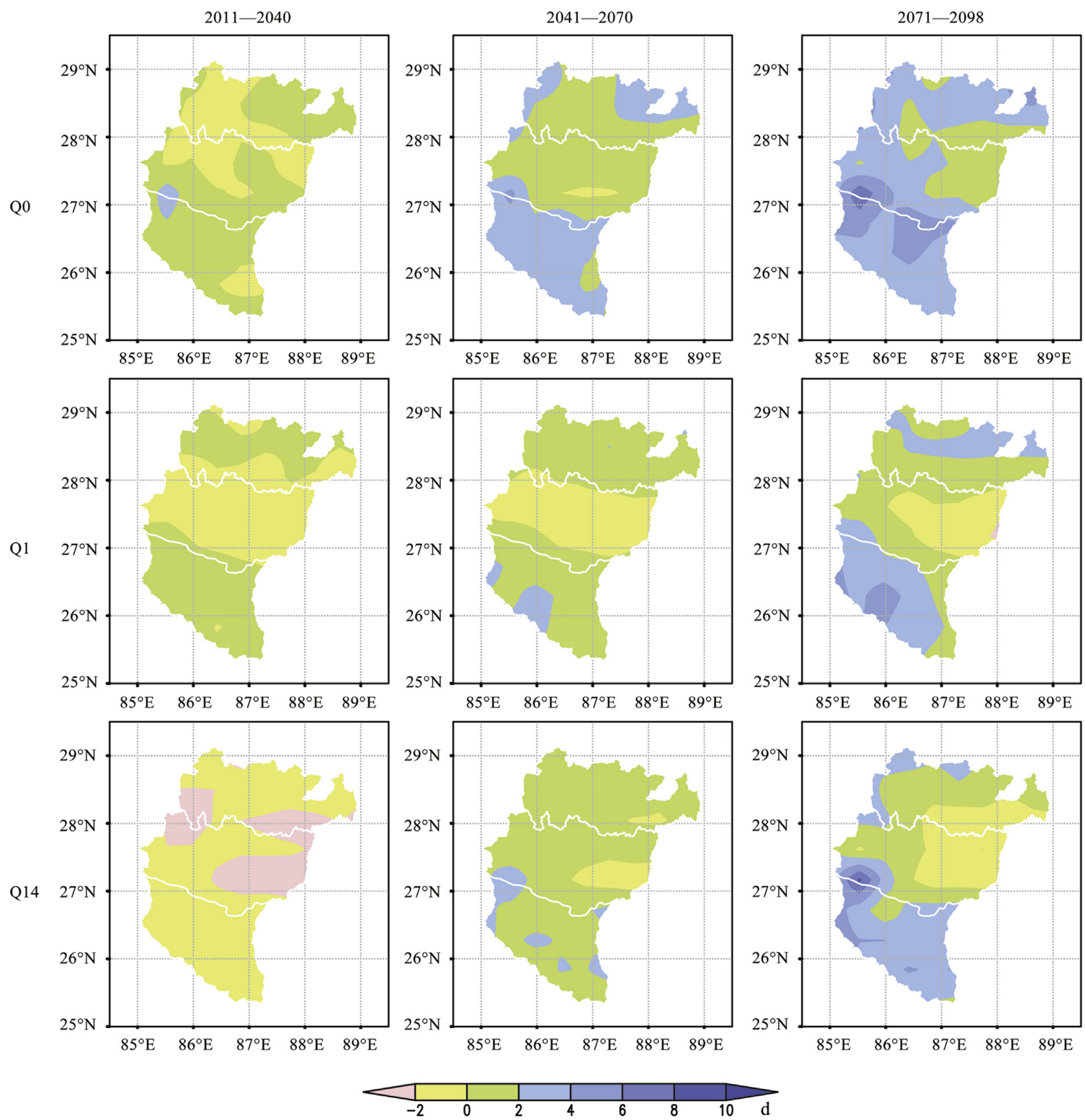


Fig. 7. Projected change in number of very wet days (95th percentile) from the base period (1961−1990).

temperature to construct a 0.25° resolution data set for maximum and minimum temperature.

### *2.4. Development of extreme indices*

The joint CCl/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) has identified 27 core indices (11 for precipitation and 16 for temperature) for the study of extreme climate events (Alexander et al., 2006; http://etccdi.pacificclimate.org/list_27_indices.shtml). Precipitation indices for frequency, intensity, consecutive dry days (CDD), consecutive wet days (CWD), and extreme wet days and very wet days (99th and 95th percentile) were analysed. We compared rainfall events with different percentile values as the rainfall distribution within the basin varies considerably and comparison with a threshold value does not make sense. Moderate and light rainfall (75th and 50th percentile) were also analysed to see if these events were complementary over Koshi basin as it was over central India, as indicated by Goswami et al. (2006). For temperature, we used the indices highest maximum, lowest minimum, warm and cold days (90th and 10th percentile of maximum temperature), and warm and cold nights (90th and 10th percentile of minimum temperature).

## 3. Results and discussion

### *3.1. Evaluation of model performance*

To evaluate the model performance, the simulated spatial distribution of the summer monsoon (June–September) rainfall in the baseline period (1961–1990) was compared

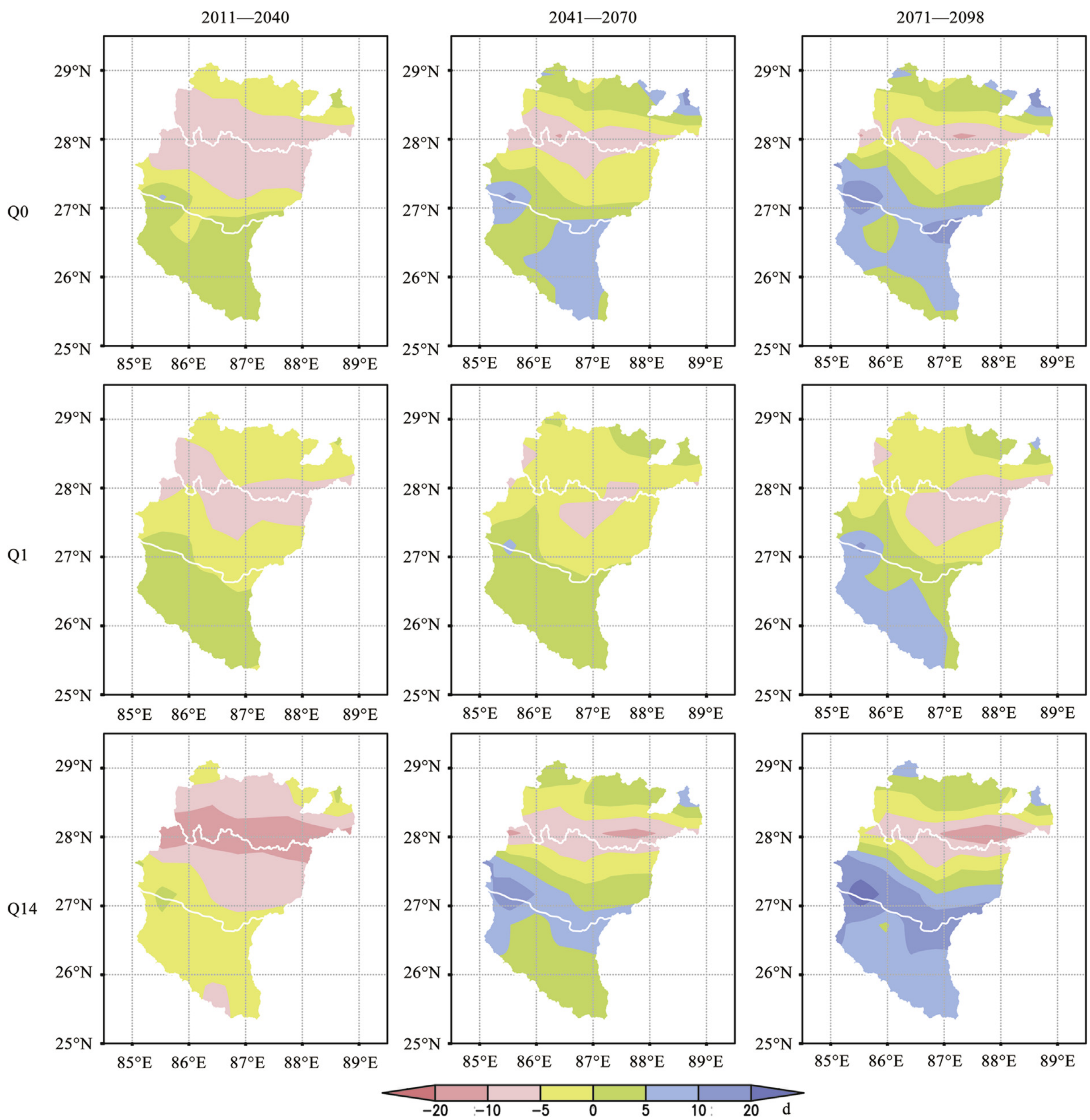


Fig. 8. Projected change in number of moderate rainfall days (75th percentile) from the base period (1961–1990).

with the APHRODITE data (Fig. 2). Basic features such as the maximum amount of rainfall being in the middle mountain area and a north-south gradient with a sharp decrease towards the north were captured by the PRECIS simulation but with some wet bias. Fig. 3 shows the average monthly values of precipitation over the basin during the baseline period. The PRECIS simulations overestimated the values in all months but captured the pattern of the annual cycle. Fig. 4 shows the comparison of the observed and simulated temperature distribution. From March to May, the Q0 and Q1 simulations were very close to the observed values while the Q14 simulation lay close to the observed values in March and June, but overestimated in April and May; in the remaining months, all model simulations underestimated compared to the observed values.

### 3.2. Future projections

The future projections for extreme rainfall and temperature obtained from the PRECIS model based on the IPCC SRES A1B scenario are shown for the three time slices 2011–2040 (near future), 2041–2070 (mid-century), and 2071–2098 (distant future) and compared with the values for 1961–1990 as baseline.

#### 3.2.1. Rainfall frequency and intensity

Fig. 5 shows the projected changes in annual frequency of rainy days (number of days with rainfall > 1.0 mm). The number of rainy days is projected to decrease over almost all of the basin with the exception of a few small areas in the middle mountains and along the border between the middle mountains and trans-Himalaya. The Q14 simulation projected a slight increase in

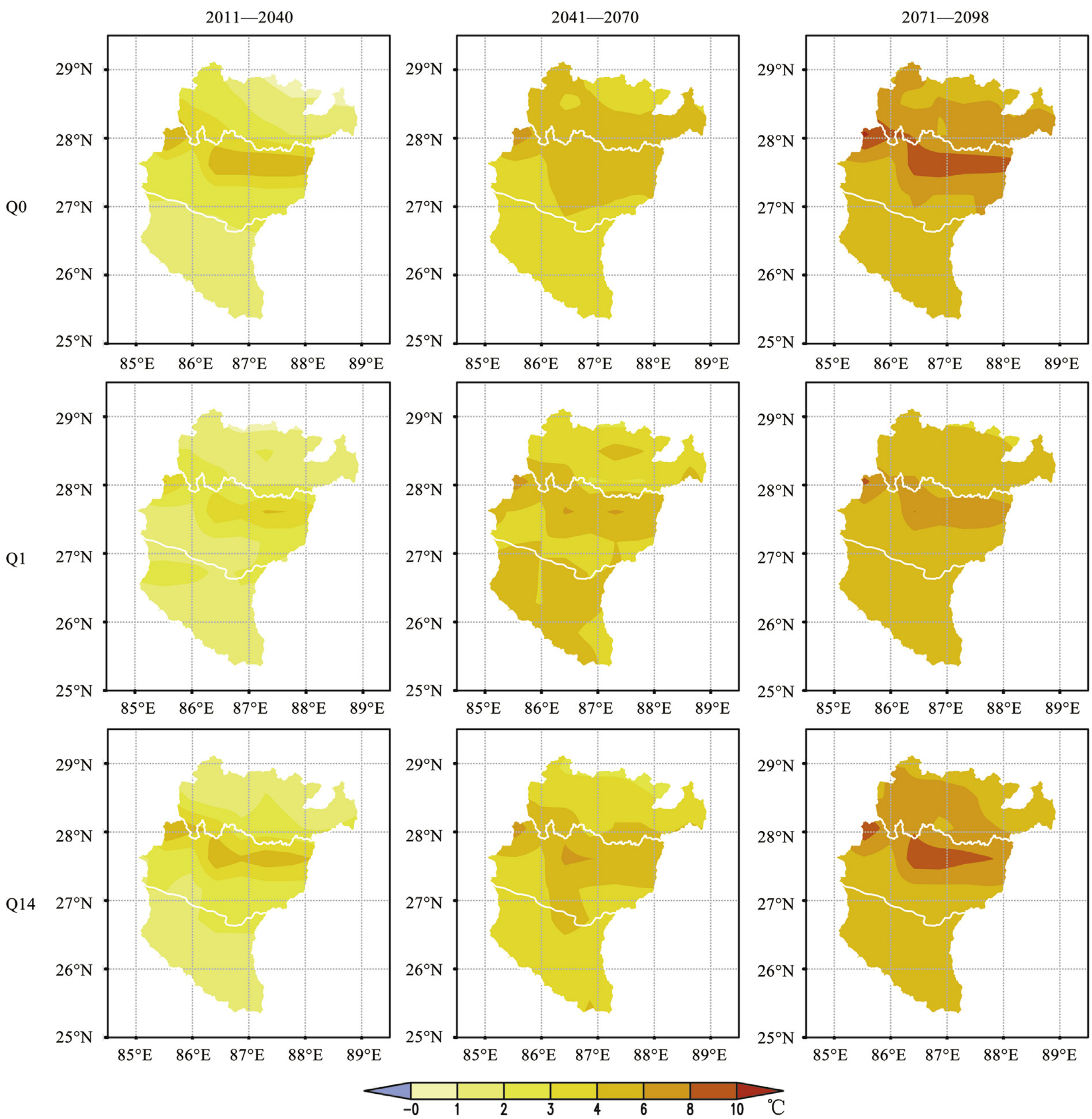


Fig. 9. Projected change in the lowest minimum temperature from the baseline (1961–1990).

rainy days over the eastern part of the middle mountain area, while all three simulations showed a decrease in the number of rainy days over the southern plains. Similarly, in the immediate future, the rainfall intensity was projected to decrease over the middle mountains and trans-Himalaya whereas in the distant future, the rainfall intensity was projected to increase over the southern plains and decrease in the border area between the middle mountains and trans-Himalaya.

### 3.2.2. Consecutive dry days (CDD)

Fig. 6 shows the projected changes in annual consecutive dry days. Overall, consecutive dry days were projected to increase in the basin, with the exception of a small area along the border between the middle mountains and trans-Himalaya. Q0 projected a decrease in all time slices. All three simulations projected an increase in CDD over the southern plains, with an increase of more than 15 d over some areas in the distant future. The consecutive wet days were projected to decrease over most of the basin except in a small area to the east of the middle mountains and trans-Himalayas (not shown).

### 3.2.3. Extreme rainfall events

Projected changes in extreme wet days and very wet days for the 99th and 95th percentile values were analysed. The 99th percentile value ranges from more than 130 mm over the middle mountains to less than 20 mm in the extreme north, projected an increase of 1−2 d by Q0 simulation while Q1 and Q14 projected a decrease by 1−2 d over most of the basin.

Changes in number of very wet days is shown in Fig. 7. The ±2 d anomalies were projected across most of the basin in the

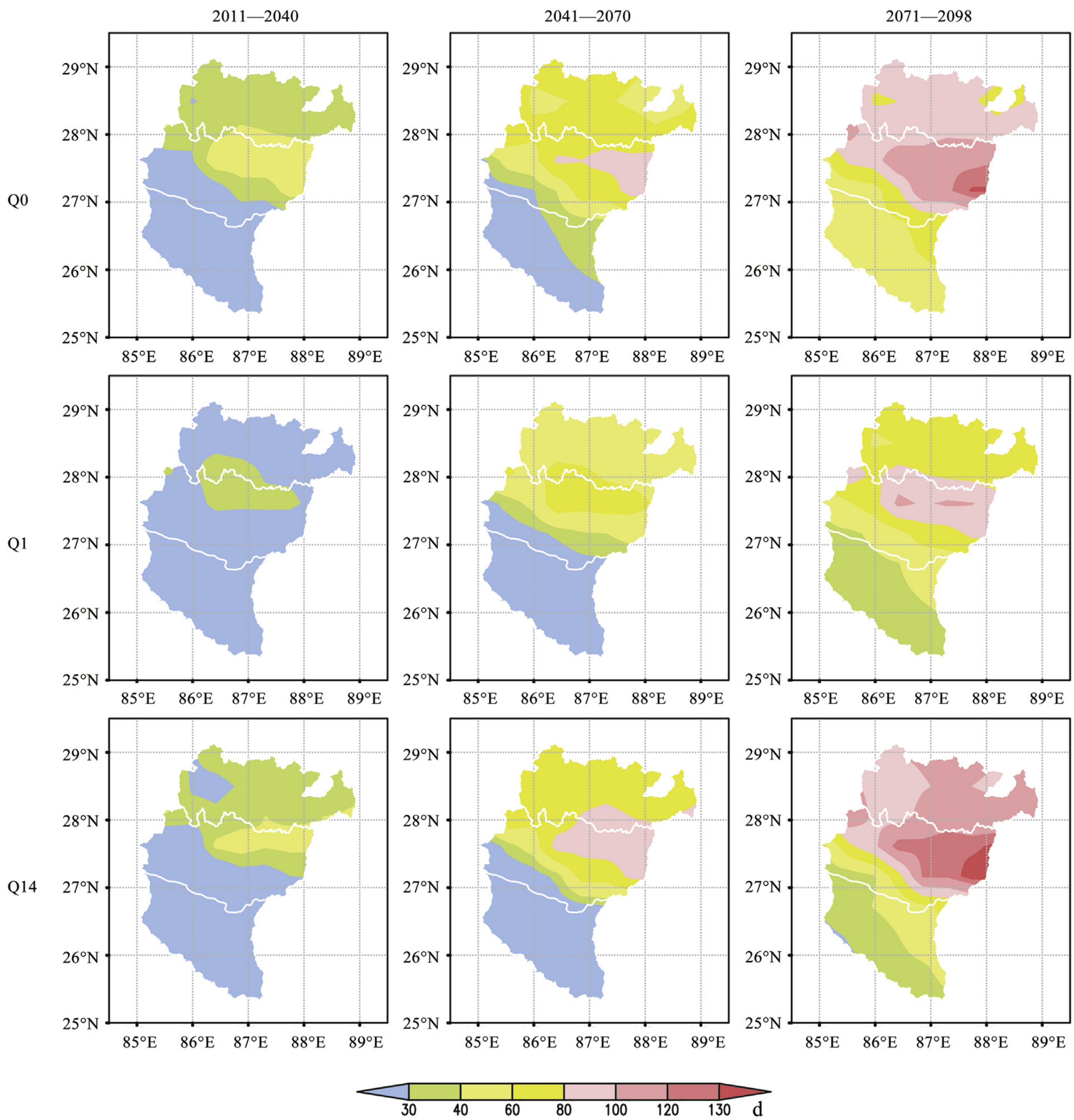


Fig. 10. Projected change in number of warm days (days with maximum temperature greater than the 90th percentile value) form the baseline (1961−1990).

near future, with increases in the distant future of 4–6 d or more over the southern plains and up to 4 d over the trans-Himalayas, and decreases in the distant future of up to 2 d over the east (Q1) or northeast (Q14) parts of the middle mountain area. Agarwal et al. (2014) also reported decreasing trend in the near future, however found no consensus among the GCMs towards mid and distant future over Koshi basin.

### 3.2.4. Moderate and light rainfall events

Fig. 8 shows the projected changes in number of moderate rainfall days,. Q0 and Q1 projected a decrease over the middle mountain and trans-Himalaya areas and an increase over the southern plain area in the near future, and Q14 a decrease throughout the basin. In the distant future, all three simulations projected an increase over the southern part of the middle mountains and the southern plains, and a decrease over the northern part of the middle mountains and southern part of the trans-Himalaya; Q1 projected a decrease over the whole trans-Himalaya, while Q0 and Q 14 projected an increase over the extreme northern part of the basin. Similarly, in the number of light rainfall days projected a decrease over the northern parts of the middle mountain and southern part of the trans-Himalaya areas.

### 3.2.5. Projected changes in the highest and lowest temperature

Both the annual highest maximum and lowest minimum temperature are projected to increase in the future. The lowest minimum temperature projected an increase in the near future up to 4 °C and 4–8 °C in the distant future (Fig. 9). Agarwal et al. (2016) also reported increase in maximum and minimum temperature in future over Koshi basin. All three simulations show a generally increasing trend with the greatest increase over the higher Himalayan area of the middle mountains, reflecting the elevation-dependent warming (EDW) phenomenon reported by many research groups in the HKH region and surrounding areas (Guo et al., 2016; Liu and Chen, 2000; Shrestha et al., 1999; Shrestha, 2008; Yan et al., 2016).

### 3.2.6. Projected changes in warm and cold days

Fig. 10 shows the projected changes in warm days. The total number of warm days is projected to increase progressively over the whole basin towards the distant future by all three simulations, with a lower increase over the southern plains and greater increase over the middle mountain and trans-Himalaya areas.

The area averaged time series of Fig. 11 shows a clear increasing trend in warm days and decreasing trend in cold days. Both trends were statistically significant at 95%. These trends were also observed in the past data and is reported by various authors (Baidya et al., 2008; Klein Tank et al., 2006; Shrestha et al., 2016). Therefore, similar trend is expected to continue in the future.

### 3.2.7. Projected changes in warm and cold nights

Fig. 12 shows the projected changes in cold nights. The total number of cold nights is projected to decrease rapidly over the

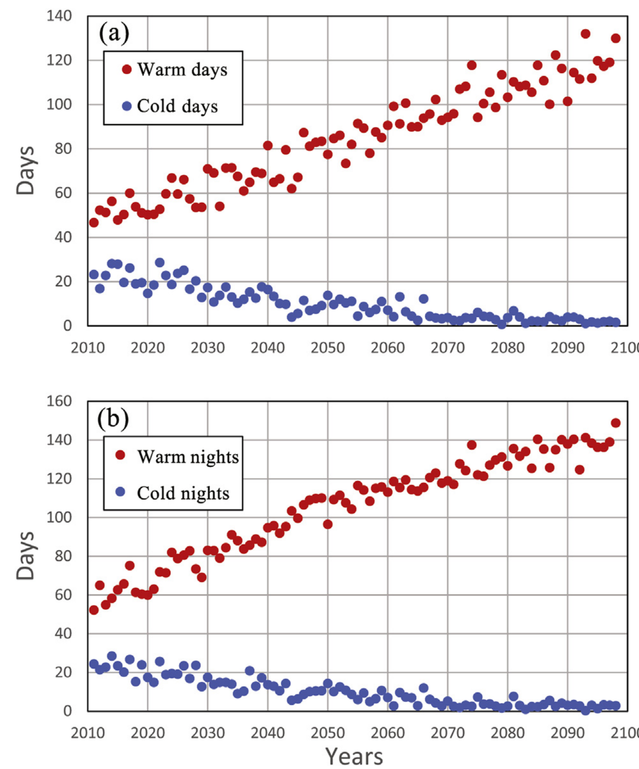


Fig. 11. Projected change (average of Q0, Q1 & Q14) over 2011–2098 in number of (a) warm days and cold days, and (b) warm nights and cold nights.

whole basin towards the distant future by all three simulations, with the greatest increase over the middle mountain area. Similarly, the total number of warm nights is projected to increase progressively over the whole basin. The area averaged time series (Fig. 11b) shows a clear increasing trend in warm nights and decreasing trend in cold nights. Both trends were statistically significant at 95%. These results are consistent with the findings of Panday et al. (2014) for the eastern Himalaya.

## 4. Conclusions

The study presents the results of projections of future changes in extreme rainfall events and extreme temperature trends over the Koshi basin prepared using the PRECIS model under the IPCC SRES A1B global warming scenario.

The results suggest that rainfall frequency will decrease overall over the basin, while the intensity is likely to increase slightly over the southern plains. The number of consecutive wet days is projected to decrease, and the number of consecutive dry days will increase, almost throughout the basin.

No secular (non-periodic) changes are projected in extreme wet days, however the number of very wet days is expected to increase overall towards the distant future, while moderate rainfall days are expected to decrease over the northern part of the middle mountains and southern part of the trans-Himalaya area.

A gradual increase is projected in both the highest temperatures and lowest temperatures, with the greatest increase over the middle-mountains and higher Himalaya. The number

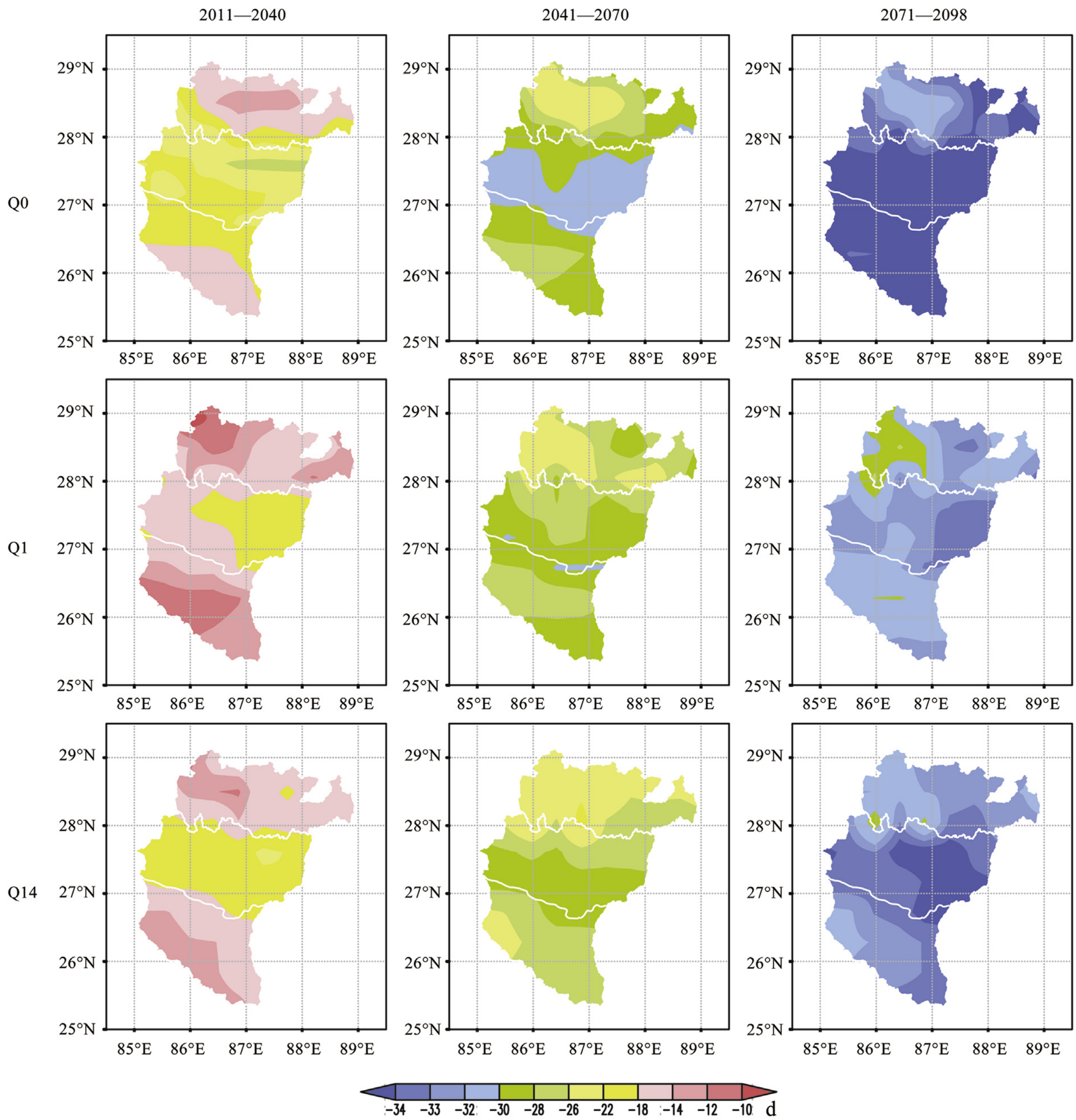


Fig. 12. Projected change in number of cold nights (days with minimum temperature less than the 10th percentile value) relative to the baseline (1961–1990) as simulated by PRECIS.

of warm days is projected to increase over the whole basin in the distant future, with a greater increase over the middle/high mountain and trans-Himalayan areas than over the southern plains, while the number of warm nights is expected to increase more over the southern plains than over the hills and mountains to the north.

The projections show the expected range of changes in rainfall and temperature from the PRECIS baseline. However, it is important to note that the projections contain significant uncertainties and were further limited by the use of a small number of simulations from a single high-resolution regional climate model. Thus the values should be seen as indicative rather than definitive.

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