Assessment of atmospheric conditions over the Hong Thai Binh river watershed by means of dynamically downscaled ERA-20C reanalysis data
C. Ho, A. Nguyen, A. Ercan, M. L. Kavvas, V. Nguyen and T. Nguyen

ABSTRACT
Long-term, high spatial and temporal resolution of atmospheric data is crucial for the purpose of reducing the effects of hydro-meteorological risks on human society in an economically and environmentally sustainable manner. However, such information usually is limited in transboundary regions due to different governmental policies, and to conflicts in the sharing of data. In this study, high spatial and temporal resolution atmospheric data were reconstructed by means of the Weather Research and Forecasting Model-WRF with input provided from the global atmospheric reanalysis of the 20th century (ERA-20C) over the Hong-Thai Binh River watershed (H-TBRW). The WRF model was implemented over the physical boundaries of the study region based on ERA-20C reanalysis data and was configured based on existing ground observation data in Vietnam’s territories, and the global Aphrodite precipitation data. With the validated WRF model for H-TBRW, the reconstructed atmospheric data were first reconstructed for 1950–2010, and then were evaluated by time series and spatial analysis methods. The results of this study suggest no significant trend in the annual accumulated precipitation depth, while there were upward trends in annual temperature at both the point and watershed scale. Furthermore, the results confirm that topographic conditions have significant effects on the climatic system such as on precipitation and temperature.

Key words | dynamical downscaling, ERA-20C, Hong-Thai Binh River watershed, transboundary region, WRF

INTRODUCTION
Atmospheric data at the regional-to-local scale is one of the crucial facts for climatology, hydrology studies, and other disciplines of the terrestrial environment (Gates 1992; Daley 1993; Giorgi et al. 2009; Ishida et al. 2017). Based on such information, it is possible to assess climate changes, water resources conditions, and develop strategic adaption with the purpose of reducing the effects of risks on human society in an economically and environmentally sustainable manner. In particular, long-term, high spatial and temporal resolution of atmospheric data are being increasingly recommended for regional hydroclimatic assessment (Ohara et al. 2010; Trinh et al. 2016a; He & Gautam 2016; Jang et al. 2017a). In spite of the importance of detailed atmospheric information, there has been limited data availability over transboundary regions due to different governmental policies, and conflicts arise in the sharing of data (Sneddon & Fox 2006; Wilk et al. 2006; Voss et al. 2013). This issue necessitates an advanced technology which is able to reconstruct and investigate atmospheric conditions over transboundary regions under limited data or no-data conditions.

Recently, there have been attempts to obtain atmospheric information from global atmospheric reanalysis...
data (Krishnamurti et al. 1997; Compo et al. 2006; Brower et al. 2013; Fuka et al. 2014). However, these global atmospheric reanalysis data are too coarse which prevents them from being used directly for local impact studies. Research efforts have thus been performed to downscale these coarse data to the scale of a studied watershed. Some recent studies on atmospheric assessment used statistical approaches (statistical or stochastic downscaling) to reconstruct historical data. Such approaches rely heavily on gauge observations. Therefore, the statistical approach is not applicable in ungauged or sparsely gauged watersheds (Anderson et al. 2007; Jang & Kavvas 2015). In addition, the stochastic methods assume stationarity in the hydroclimatic regime, and do not account for the ongoing change in the world’s hydro-climate conditions (Milly et al. 2008; Trinh et al. 2016b). Consequently, the statistical downscaling approach has not been effective for investigating atmospheric conditions in limited data conditions and under changing atmospheric conditions. The alternative method, dynamical downscaling (DD), uses conservation equations of mass, momentum, and energy in the form of a regional climate model (RCM) to spatially and temporally refine future atmospheric conditions. This approach is known as a suitable technology for areas with complex topography, and for estimating atmospheric data under limited data or no-data conditions (Kavvas et al. 2015; Jang et al. 2017b).

In this context, this study applies the DD technique with input provided from the European Centre for Medium-Range Weather Forecasts (ECMWF) – Atmospheric Reanalysis coarse climate data of the 20th century (ERA-20C) to reconstruct atmospheric data including precipitation, temperature, and wind speed at fine spatial and time resolutions. The ERA-20C was selected since it provides three-dimensional data at 3-hour time increments for the required atmospheric and surface variables throughout the 20th century (Poli et al. 2013, 2015, 2016). In addition, this dataset is long enough, stable, and continuous, and can uniformly cover the globe at a spatial resolution of 1.25° (∼165 km) at the equator and capture consistently dry and wet events. Due to its coarse scale atmospheric data, ERA-20C was first dynamically downscaled to a fine spatial resolution over the studied watershed (<10 km) by means of the Weather Research and Forecasting (WRF, Skamarock et al. 2005) model. The downscaled atmospheric data were then used to investigate atmospheric conditions over the target region.

The selected study region, Hong Thai Binh River watershed including upstream and downstream parts, is a transboundary region between China, Vietnam, and Laos. The upstream sector is located in China with 48.8% of the watershed area, while the downstream sector is located in Vietnam and Laos with 50.3 and 0.9% of the watershed area respectively. Due to no formal data sharing agreement between these countries, there has been limited data availability over this transboundary region. In order to assess the atmospheric conditions over the Hong Thai Binh river watershed, the WRF model was implemented based on the physical boundaries of the study region and ERA-20C reanalysis data, and was configured based on existing ground observation data in Vietnam, and Aphrodite precipitation data version of APHRO_V1101 datasets for monsoon Asia (APHRODITE) (Yatagai et al. 2009, 2012). After successfully configuring and evaluating the WRF model, the WRF model could produce historical atmospheric data at a fine spatial resolution over the Hong Thai Binh river watershed including China and Vietnam’s territories. The historical fine time space atmospheric data were analyzed with the purpose of identifying historical trends and characteristics in space and time, by means of statistical analyses. Such information is meaningful for strategic planning and climate change adaption in the water resources management of the Hong River watershed. The reconstructed data can also be used as input to the watershed hydrology and environmental modeling for reconstruction and assessment of hydrologic and environmental conditions over the target region.

**STUDY REGION**

The Hong-Thai Binh River watershed (H-TBRW) or Red River watershed is located in Northern Vietnam (downstream sector) and Southwest China (upstream sector) with a catchment area of 169,020 km² (Figure 1). The H-TBRW is considered as one of the largest international rivers in Vietnam. The H-TBRW is bordered by Yangtze River basin from the North, Mekong basin from the West, Gulf of Tonkin from the East, and Ma River from the South. The topography of the watershed slopes from...
northwest to southeast. Mountainous terrain over the east and north dominates the upper catchment area and tends to decrease in a northwest–southeast direction with an average altitude of 1,090 m. Within the H-TBRW, Hoang Lien Son mountains divide the H-TBRW into Da and Thao-Lo River watersheds, which are the tributaries of the Red River. Due to its large area, average annual precipitation in H-TBRW is spatially distributed in a wide range over H-TBRW (from 100 to 1,800 mm), and the rainy season lasting from May through October represents 85–90% of the total annual rainfall, and the dry season from November to April represents only 10–15% of the total annual rainfall. Wind direction in this area depends on the orientation of the valley. It can vary from mainly the west or northwest during the summer in the Da River watershed to south-southeast in the Lo River watershed. Together with topography, wind speed heavily affects the distribution of rainfall in the watershed. The land use and land cover are diverse from upstream to downstream. Mostly, the area is covered by crops and forests. Industrial crops dominate (58%) in the Lo River watershed, forests and bare land (74%) in the Da River watershed, and paddy rice fields (66%) in the delta area. The Thao River watershed is characterized by a larger diversity in land use including forest, paddy rice fields, and industrial crops (85%) (Ho 2018).

Along with Mekong River watershed, the H-TBRW is a key economic and agricultural region in Vietnam. The main economies of the region are industry, services, agriculture, forestry and fisheries. Therefore, climatic variations and changes in and around H-TBRW not only have a significant effect on natural systems, but also on social systems and economies of this region.

DATA AND MODEL IMPLEMENTATION

In this study, the historical reanalysis data, ERA-20C, was selected for setting up the initial and boundary conditions in WRF simulations to derive finer scale variables over H-TBRW. ERA-20C was developed in the European Centre for Medium Range Weather Forecasts with the same surface and atmospheric forcing as the final version of the atmospheric model integration ERA-20CM (Hersbach et al. 2013, 2015). The spatio-temporal evolution of ERA-20C includes 91 atmospheric vertical levels between the surface and 0.01 hPa, four soil layers of the land surface, 25
frequencies and 12 directions of ocean waves. The ERA-20C is a public dataset and is available for downloading directly from its associated organizations. For a description of the contents of ERA-20C, see Hersbach et al. (2015).

Based on ERA-20C and physical boundaries of the H-TBRW, WRF was employed to dynamically downscale coarse scale ERA-20C atmospheric data to the scale of the studied watershed. Figure 1 depicts three nested domains used for the WRF simulations. The spatial resolution of each of the nested domains is one-third of that of its parent domain. The first domain (D1) has a spatial grid resolution of 81 km with 26 × 29 horizontal grid points, the second (D2) is 27 km with 48 × 57 horizontal grid points, the third (D3) is 9 km with 105 × 78 horizontal grid points. In order to simulate atmospheric processes in each domain, parameterization options in the WRF model need to be configured for all three domains. The selected physical parameterizations are the Goddard scheme (Tao et al. 1989) for the microphysics processes option, the new Simplified Arakawa–Schubert scheme (Han & Pan 2011) for the cumulus parameterization option, BouLac scheme (Bougeault & Lacarrere 1989) for the planetary boundary layer option, the New Goddard scheme (Chou & Suarez 1999) for both the short-wave and long-wave radiation options, and the RUC Land Surface Model (Benjamin et al. 2004) for the land surface model option (Table 1). The initial and boundary conditions for the climate variables over H-TBRW were set up by means of WRF based on ERA-20C reanalysis data at 3-hourly intervals.

Two observation datasets were used for evaluation of WRF simulations. One is ground observation data that were taken from the Vietnam Center of Hydro-Meteorological Data (VCHMD). These ground observation data include 111 meteorological stations covering the area of H-TBRW in Vietnam, as shown in Figure 1. The other dataset is the global high resolution (0.25°) dataset for precipitation, APHRODITE, developed by the Research Institute for Humanity and Nature (RIHN) and the Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA), Japan (www.chikyu.ac.jp/precip/) (Yatagai et al. 2012). First, the downscaled precipitation data by WRF was compared with corresponding ground observations from the meteorological data in the downstream part of H-TBRW. Figure 2 shows the comparison of ground observations and model-simulated monthly basin average precipitation over H-TBRW. Figure 2 shows the comparison of ground observations and model-simulated monthly basin average precipitation over H-TBRW during 1990–2000. It is noted that the basin average precipitation over H-TBRW in Vietnam was calculated from the data of 111 VCHMD meteorological stations using the Thiessen polygon method (Figure 3). This comparison shows the goodness of fit of the modeled simulation to the corresponding observations based on the correlation coefficient (R), and Nash–Sutcliffe efficiency coefficient. The correlation coefficient and the Nash–Sutcliffe coefficient are 0.89 and 0.782, respectively, for the study watershed, suggesting that the simulated monthly precipitation data are highly correlated and well matched to the ground-observed monthly precipitation data. The WRF model simulations also can be compared against different observation stations, as shown in Figure 4. Six sample meteorological stations were selected for these comparisons over 10 years (1990–2000) and their locations are shown in Figure 1. The six meteorological stations are distributed through the downstream part of H-TBRW and are at different elevations (Ha Giang 196 m, Muong Te 540 m, Lai Chau 648 m, Quynh Nhai 395 m, Hiep Hoa 16 m, Hoa Binh 24 m). There is a good agreement in all comparisons since the model-simulated precipitation matches the corresponding observation data well with respect to magnitude, as shown in Table 2. For temperature comparisons, Nash–Sutcliffe efficiency values are larger than 0.85, which shows an excellent match between the model simulation and the corresponding observation data.

Due to unavailability of atmospheric observation data over the upstream part of H-TBRW in China’s territories, the WRF simulations can be evaluated based on the global

<table>
<thead>
<tr>
<th>Table 1</th>
<th>WRF model configuration</th>
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<tr>
<td><strong>WRF model configuration</strong></td>
<td><strong>The selected option</strong></td>
</tr>
<tr>
<td>Microphysics processes</td>
<td>Goddard scheme (Tao et al. 1989)</td>
</tr>
<tr>
<td>Cumulus parameterization</td>
<td>New Simplified Arakawa-Schubert Scheme (Han &amp; Pan 2011)</td>
</tr>
<tr>
<td>Planetary boundary layer scheme</td>
<td>BouLac scheme (Bougeault &amp; Lacarrere 1989)</td>
</tr>
<tr>
<td>Radiation scheme</td>
<td>New Goddard scheme (Chou &amp; Suarez 1999)</td>
</tr>
<tr>
<td>Surface scheme</td>
<td>RUC Land Surface Model (Benjamin et al. 2004)</td>
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</tbody>
</table>
high resolution (0.25°) precipitation datasets, the APHRODITE. The spatial distribution of the mean monthly of the WRF-simulated historical precipitation fields and the corresponding precipitation fields from APHRODITE data were calculated over H-TBRW and were also compared for evaluating the model performance, as shown in Figure 5. In general, the model-simulated precipitation matches the corresponding APHRODITE data well with respect to magnitude and the spatial distribution during the years from 1990 to 2001. However, there are slight differences in this comparison because APHRODITE is a spatial precipitation data set that is interpolated from the ground-based observations that are mostly located at easily accessible and relatively low-elevation areas (Kure et al. 2013). Therefore, it is suspected that APHRODITE data may underestimate the precipitation at high-elevation locations. This validation confirms that the atmospheric simulations of the WRF can successfully produce historical
climate data over H-TBRW in both the upstream and downstream areas.

ASSESSMENT OF ATMOSPHERIC CONDITIONS OVER THE TRANSBOUNDARY REGION–HONG THAI BINH RIVER WATERSHED

After configuring the WRF model options, the historical downscaled atmospheric data were simulated and then evaluated over H-TBRW. The historical atmospheric variables including precipitation and temperature were assessed in terms of statistical and spatial analyses. The statistical approaches investigated in this study include time series, and trend analyses which have been widely applied in the assessment of atmospheric conditions. Such information can indicate climate change impacts on hydro-meteorological conditions and is meaningful for both long- and short-term water resources management. The atmospheric conditions can...
be spatially analyzed to identify hydro-meteorological distribution over the whole study domain. It is noted that there were 8910 simulated atmospheric data grids reconstructed during 1950–2010 at 9 km resolution (Figure 1).

Table 2 Statistical test values of WRF-simulated and VCHMD monthly precipitation (P) and temperature (T) during 1990–2001 at the six meteorological stations

<table>
<thead>
<tr>
<th>Atmospheric variables</th>
<th>Ha Giang</th>
<th>Lai Chau</th>
<th>Hoa Binh</th>
<th>Hiep Hoa</th>
<th>Muong Te</th>
<th>Quynh Nhai</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.743</td>
<td>0.988</td>
<td>0.852</td>
<td>0.978</td>
<td>0.812</td>
<td>0.980</td>
</tr>
<tr>
<td>Nash–Sutcliffe coefficient</td>
<td>0.553</td>
<td>0.952</td>
<td>0.711</td>
<td>0.865</td>
<td>0.542</td>
<td>0.947</td>
</tr>
</tbody>
</table>
Assessment of precipitation over H-TBRW during 1950–2010

Basin average precipitation data were first analyzed in terms of annual precipitation during 1950–2010, and then depicted as 10-year moving averages of annual precipitation to determine overall changes, as seen in Figure 6. In statistics, a moving average is a measure to average different subsets of a full dataset, and can distinguish an overall trend in a dataset. By visual inspection of the 10-year moving averages, it is seen that there were no significant trends in annual precipitation over H-TBRW. This result was confirmed by the Mann-Kendall trend test that showed a P-value (0.39) that is greater than the significance level alpha = 0.05 (at 95% confidence level), thus no trend was found in the basin average of annual precipitation.

Figure 5 | Comparison of model-simulated precipitation and APHRODITE data over the study region from 1990 to 2001 at a resolution of 0.25°.

Figure 6 | Annual basin average precipitation depths over H-TBRW during 1950–2010 with their 10-year moving averages.
during 1950–2010 over H-TBRW. The Mann–Kendall trend analysis was also applied to the selected six meteorological stations. The test results, including the slope and the standard error of the trend line, as well as the P-value of the Mann–Kendall trend test, are shown in Table 3. Consequently, the Mann–Kendall trend test results indicate no significant trends in annual precipitation depths at any of the six meteorological stations.

In order to analyze changes in the precipitation regime during 1950–2010, the monthly climatology basin average of annual precipitation was then divided into two time windows of 30 years, 1950–1980 and 1981–2010, as shown in Figure 7. It is also clearly seen from this figure that the wet season lasts for six months from April to September, and the dry season occurs from October to March of the following year. As shown in Figure 7, there is no significant difference, and no shifting season between the first and second time windows at both dry and wet seasons. Statistical analyses were performed on the monthly climatology basin average annual precipitation for each time window. The results of this analysis are presented in Table 4. The basin average annual precipitation increased about 1.4% from the period 1950–1980 to 1981–2010, whereas the standard deviation decreased 3.5%. This result confirms that no significant difference in the statistical characteristics of precipitation was found between the first and second time windows over H-TBRW.

To identify the precipitation distribution for the whole study region, the monthly climatology precipitation spatial distribution maps for the study period (1950–2010) are shown in Figure 8. It is noted that all grid data (8190 grids) from the third domain (D3) were used for this purpose. This figure presents precipitation spatial distribution for each month with the largest precipitation typically occurring in June, and the lowest precipitation in January.

It is worth noting that high intensity precipitation often occurs over the high elevation area such as the mountain ranges. This phenomenon can be clearly seen in precipitation distribution maps from May to September, since there was more precipitation in the upstream of the watershed than the downstream sector. This phenomenon can be explained by different elevations between the two regions since the upstream sector is located in the mountainous area with elevations higher than 800 m where high intensity precipitation occurs, while the downstream sector elevations are mostly less than 400 m. Along with differences of precipitation between the upstream and downstream areas, there were precipitation differences between the west and the east of the Hoang Lien Son mountain range. From visual inspections of precipitation distribution maps from June to August, it may be inferred that the high intensity precipitation area occurred in the west of Hoang Lien Son mountains range where the Da River watershed is, the largest sub-watershed in the H-TBRW. In order to explain this phenomenon, the surface winds (zonal (u10) and meridional

| Table 3 | Slope and standard error of the trend line of the annual precipitation at the selected six meteorological stations with P-value of the Mann–Kendall trend test in parentheses at the 95% confidence level |
|---------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Ha Giang | Lai Chau | Hoa Binh | Hiep Hoa | Muong Te | Quynh Nhai |
| 0.05 ± 0.296 (0.296) | 0.15 ± 0.052 (0.052) | 0.89 ± 0.411 (0.411) | 0.69 ± 0.419 (0.419) | 0.12 ± 0.663 (0.663) | 0.211 ± 0.152 (0.152) |

| Table 4 | Summary statistics for the basin average annual precipitation in two time windows, 1950–1980 and 1981–2010, over H-TBRW |
|---------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Period | Basin average of annual precipitation (mm) | Standard deviation (mm) | Skewness coefficient |
| 1950–1980 | 140.44 | 116.19 | 0.302 |
| 1981–2010 | 142.52 | 112.14 | 0.455 |
winds \((v10)\) at 10 m above ground) over the study domain (D3) during 1950–2010 are shown in Figure 9. This figure shows average wind speed and direction distribution maps over the study domain in June, July, and August during 1950–2010. In this period, the summer monsoon is active, and the strong winds flow mostly in the northeast direction. This active monsoon pushes precipitable water from southwest to northeast and causes precipitation since precipitable water hits the Hoang Lien Son mountains range. Consequently, precipitable water falls mostly in the Da River watershed that is located in the west of Hoang Lien Son mountain range. These results point to the important role of
Hoang Lien Son mountain range in the assessment of precipitation regime over the study region.

Another important issue is the change in precipitation distribution maps for the 30-year time windows. In order to identify the changes in precipitation at every location in the domain, Figure 10 shows the spatial maps of the precipitation change between the first and the second time windows, i.e. 1950–1980 and 1981–2010. Absolute changes in precipitation seem to be large in the wet seasons (May–September), while there is no significant change in the dry seasons. These results point to the importance of physically based applications in hydrometeorology studies, as this application can describe the change in precipitation through both time and space.

Assessment of temperature over H-TBRW during 1950–2010

For the assessment of temperature, similar statistical analyses were applied over the H-TBRW during 1950–2010. Figure 11 shows annual basin average temperature over H-TBRW with 10-year moving averages. From the analysis of the 10-year moving averages, it is seen that temperature is increasing. The 10-year moving average of annual temperature increased by 5.7% (21.2–22.5 °C) over H-TBRW over the 61 years (1950–2010). This increased trend was confirmed by the Mann–Kendall trend analysis with a P-value (0.0001) less than the significance level alpha = 0.05 (at 95% confidence level). In terms of the comparison of temperature between two time windows of 30 years, 1950–1980 and 1981–2010, it may be inferred from Figure 12 that the temperature is increasing in every month with the temperature magnitude growing by 1–6% from the first time window to the second time window. It is also noted that there is no shifting season between the first and second time windows at both cold and hot seasons. Statistical analyses on monthly climatology basin average of annual temperature for each time window are presented in Table 5.

Temperature is one of the most vulnerable variables in the atmospheric cycle with respect to climate change. Additional evaluations of temperature spatial distribution maps are also useful to identify the regions that are most
sensitive to climate change. In addition, these circulation features are also important as they are contributing factors to rainfall dynamics. To identify the regions that are most sensitive to climate change, monthly climatology temperature spatial distribution maps for the two 30-year time windows are exhibited in Figure 13. All of the maps in these figures present evidence of heterogeneity in temperature conditions over H-TBRW since the temperature of the downstream sector is significantly higher than that of the upstream sector in both time windows. This analysis confirms that the atmospheric conditions are quite different between the upstream sector of H-TBRW (China’s...
territories) and the downstream sector (Vietnam’s territories). For comparison of the two 30-year non-overlapping time windows for temperature, Figure 14 presents the relative changes between the climatology of temperature spatial distribution maps for January, April, and July between the first and the second time windows. Comparison of the monthly climatology of temperature spatial distribution maps for January, April, and July confirms an increasing trend from the first and the second time window, since the relative changes mostly show a positive value for the whole domain. Based on this map, it is possible to identify regions that are sensitive to climate change. Such information may be useful for strategic climate adaption with the purpose of reducing the effects of risks on human society in an economically and environmentally sustainable manner.

**SUMMARY AND CONCLUSIONS**

This study describes the historical changes in atmospheric conditions over the H-TBRW (approximately 169,020 km²) during 1950–2010. The data are quality controlled by the numerical regional climate model WRF based on its input provided from the global reanalysis data – ERA20C. Due to no formal data sharing agreement among different countries, there has been limited data availability over this transboundary region. The downscaled precipitation data from WRF simulations were compared against available observations in Vietnam’s territories and from global Aphrodite precipitation data. The simulations matched the precipitation observations well with respect to magnitude and spatial distribution at both point location and the watershed scale. From these results, it is concluded that the application of WRF over the transboundary region H-TBRW is successful.

With the WRF for H-TBRW validated, it is possible to reconstruct atmospheric data over the watershed, based

<table>
<thead>
<tr>
<th>Period</th>
<th>Basin average of annual temperature (°C)</th>
<th>Standard deviation (°C)</th>
<th>Skewness coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950–1980</td>
<td>21.73</td>
<td>4.27</td>
<td>-0.47</td>
</tr>
<tr>
<td>1981–2010</td>
<td>22.34</td>
<td>4.31</td>
<td>-0.49</td>
</tr>
</tbody>
</table>
on dynamically downscaled global reanalysis data – ERA20C. The simulation results provide atmospheric data at every grid point over H-TBRW at 9 km resolution including the areas of China and Vietnam. The dynamically downscaled precipitation and temperature were then evaluated at point location scale and watershed scale with both spatial and time series analyses. From the time series analysis of modeled results both at point location and watershed scale, it is found that there is no significant trend in the annual accumulated precipitation depth at the basin average, the selected six meteorological stations, and over the study watershed, while upward trends in annual temperature were detected at both point location and watershed scale. The time series analysis results in this study indicate that there may be differences in trends between annual precipitation depths and annual temperature at watershed-scale during the second half of the 20th century. From a scientific perspective, the increase in temperature over H-TBRW (about 6%, ~1.2 °C) is an evidence of recent climatic warming, and this change did not affect the precipitation condition significantly over the watershed.
The downscaled precipitation and temperature also were constructed in terms of the monthly climatology spatial distribution maps for 1950–2010, and for two consecutive non-overlapping 30-year time windows. The results indicated that the intensity of precipitation is directly proportional to elevation. This phenomenon can be clearly seen in precipitation distribution maps from May to September in Figure 8. These results also point to the important role of Hoang Lien Son mountain range in separating precipitation distribution since there were high intensity precipitation mostly occurring in the west of Hoang Lien Son mountain range, while the precipitation intensity over the east is relatively smaller. The spatial distribution of temperature is consistent with previous time series analysis. There is an increasing trend in temperature by 6% at most grid points over the H-TBRW. All of the temperature maps in these figures present evidence of heterogeneity in the temperature condition in H-TBRW since the temperature of the downstream sector is significantly higher than that of the upstream sector in both time windows. This analysis confirms that the atmospheric conditions are quite different between the upstream sector of H-TBRW (China’s territories) and the downstream sector (Vietnam’s territories). Based on the analyses in this study, it is possible to identify changes in precipitation and temperature both in time and space over the study region during 1950–2010. Such information may be useful for climate strategic adaptation with the purpose of reducing the effects of risks on human society in an economically and environmentally sustainable manner.

The results of this study can then be used as inputs to hydrological modeling for the reconstruction and assessment of hydrologic conditions over the study region. Furthermore, the calibrated and validated WRF model for H-TBRW can be utilized for the projection of future water supply from the watershed under atmospheric inputs from the global climate models’ future climate projections.

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