Detection and attribution of reference evapotranspiration change (1951–2020) in the Upper Yangtze River Basin of China
Manlin Wang, Yu Zhang, Yan Lu, Xulong Gong and Li Gao

ABSTRACT
Reference evapotranspiration (ET0) indicates atmospheric evaporating capability over a hypothetical reference surface. ET0 is an important hydrological and meteorological variable to reflect climate change. This is particularly true for the Upper Yangtze River Basin (UYRB), which is vulnerable and sensitive to changing environment. This study aims to provide a newer and longer description of ET0 change and the causes at basin and subbasin scales in the UYRB. Based on the observed data from 1951 to 2020, ET0 in the entire UYRB and subbasins is estimated using the Penman–Montieth method with local calibration. The spatial–temporal characteristics in ET0 change are identified from time-series analysis. Our results show that ET0 increases significantly by 3.3 mm/year in the entire UYRB. Stations with significant increases in annual ET0 are concentrated in the central part of the UYRB, where the mean annual ET0 is low. We further propose an improved method to assess the causes of ET0 change. Our results suggest that the relative humidity decrease has the most dominant effect, causing 4.69 mm/year of ET0 increase. Temperature increase tends to cause 1.26 mm/year of ET0 increase. Sunshine duration decrease and wind speed decrease contribute to 1.96 and 0.48 mm/year of ET0 decrease.

Key words | attribution analysis, climate change, reference evapotranspiration change, sensitivity analysis, the Upper Yangtze River Basin

HIGHLIGHTS
- ET0 increases significantly in the UYRB.
- The significant increases of annual ET0 gather in the central region of the UYRB.
- The relative humidity decrease has the most dominant effect on ET0 increase in the UYRB.
- The ET0 change and contributions of climatic variables vary in subbasins.

INTRODUCTION
Global climate change has occurred in recent decades (Sippel et al. 2020). Under climate change, regional hydrological cycles have changed in different degrees (Zhang et al. 2020). Evapotranspiration is a special hydro-climatic variable, which is a key process in the water cycle, as well as an important component of energy budget in the land–atmosphere interaction. It is the only term that links the water balance and energy balance (Xu et al. 2006). Therefore, the study of regional evapotranspiration change is helpful to understand the regional climate change and its impacts on the hydrological cycle (Song et al. 2018; Pour et al. 2020; Yaseen et al. 2020).

The terms commonly used to describe evapotranspiration include pan evaporation (Epan), actual evapotranspiration (Ea), etc.
ET₀, potential evapotranspiration (ETₚ), and reference evapotranspiration (ET₀). Eₚan is the evaporation from the free water surface of an evaporation pan, which is the most direct observation for evaporation. The pan evaporation method has been used extensively to estimate evaporation from lakes and reservoirs. ET₀ reveals the actual amount of evapotranspiration, which is the most complicated component of the water cycle. It depends on climatic factors, vegetation, soil, and amount of available water and is hard to measure (Yaseen et al. 2020). ETₚ was first introduced by Thornthwaite (1948) and formally defined by Penman (1956) gave as ‘the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile’. However, there is not an exact description of land-surface condition in this definition of ETₚ. To make it more standardized and clearer, ET₀ was further introduced, which is defined as ‘the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹ and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground’ (Wang et al. 2012). ET₀ was further studied by researchers and recommended by the Food and Agriculture Organization (FAO). ET₀ describes the evaporation capacity of the atmosphere at a specific location and time and is able to be calculated directly from meteorological data. Furthermore, there is a good consistency between Eₚan and ETₚ (Ghorbani et al. 2018; Nourani et al. 2019), and the ET₀ is usually estimated based on ET₀ (Nagler et al. 2013; Guo et al. 2016; Akhavan et al. 2019). Therefore, ET₀ is an excellent indicator for studying the evapotranspiration change and its causes (Jing et al. 2019). Statistical analysis and Geographic Information System (GIS) spatial analysis methods are commonly used in existing studies on the detection of spatial and temporal variability of ET₀. The recovered stationary series method is employed to assess the contribution of climatic variables to ET₀ change, which is employed as follows: (1) the trend in a climatic variable was removed to obtain a stationary time series; (2) ET₀ was recalculated by using the detrended data series, while original data for other variables were retained in each time; (3) the ET₀ values from the detrended and original time series were compared, and the difference was considered as the contribution of that variable to ET₀. However, when there is an abrupt change point in one climatic variable series, this method may misestimate the changes in climatic variables, especially when the time series is long (Xu et al. 2006; Qasem et al. 2019; Malik et al. 2020).

The Yangtze River is the longest river in Asia and the third-longest in the world. Water resources and hydropower resources of the Yangtze River are the most abundant in China. The Upper Yangtze River Basin (UYRB) is the streamflow formation area and hydropower storage area, accounting for 45% of basin water resources and 90% of basin hydropower resources, which has an irreplaceable position and inestimable value in China’s strategic reserve of resources (Zhang et al. 2020). Recently, measured precipitation and runoff in most regions of the UYRB have been reported changing obviously, which has great impacts on economic development, social stability, and ecological security (Zhang et al. 2018; Qi et al. 2019; Qin et al. 2020; Zhong et al. 2020). The sensitivity of hydrological projection to ET₀ depends on climatic stage. Hydrological projection is generally more sensitive to ET₀ under humid climate (Weiland et al. 2012; Dakhlaoui et al. 2020). Therefore, identifying ET₀ change and assessing the contribution of climatic variables helps to understand the climate change and its impact on the hydrological cycle in the UYRB. Some scholars have conducted studies on the ET₀ change in the Yangtze River Basin. Xu et al. (2006) employed the Penman–Monteith method to analyze the spatial distribution and temporal trend of ET₀ and Eₚan in the Yangtze River Basin based on the data from 1950 to 2000. Gong et al. (2006) analyzed the sensitivity of ET₀ to key climatic variables in the Yangtze River Basin during 1960–2000. Wang et al. (2007) investigated the upper and mid-lower Yangtze River basin trends of Eₚan and ET₀ from 1961 to 2000 using daily data of 115 stations. Most previous studies were carried out on ET₀ change before 2000 in the Yangtze River Basin. The pattern of change may have varied due to climate change, making it difficult for the previous studies to explain the recent changes in the UYRB.

Recognizing the above concerns, in this study, the ET₀ in the UYRB during 1951–2020 is estimated by using the Penman–Monteith (Song et al. 2018) method. Spatiotemporal changes in ET₀ are detected to describe the regional climate change and its impact on the hydrological cycle.
We aim to use the newest data to update the existing studies mentioned above, providing a newer description of \( \text{ET}_0 \) change. An attribution analysis method is proposed to quantify the impacts of changes in climatic variables on \( \text{ET}_0 \). The sensitivity analysis is conducted to help further explore the causes of \( \text{ET}_0 \) change. Considering the extent of the paper, other forcings than the studied ones in the paper are not considered. This paper presents the early results of our ongoing study on adaptive regulation for the water resources system under changing environment. The results of \( \text{ET}_0 \) change provide important inputs of hydrological modeling under climate change.

**STUDY AREA AND DATA PROCESSING**

The UYRB is located between 90–112°E and 23–35°N, as shown in Figure 1, with a drainage area around 10,000 km². The UYRB experiences two different typical landforms. The western part is located over the Qinghai–Tibet Plateau and Hengduan Mountains with elevations higher than 3,000 m, while the southeastern part is located in the valley with elevations under 500 m. The complex landforms gave birth to the upper reaches of the Yangtze River. Based on the major rivers and watersheds, the UYRB is divided into the Jinsha River Basin (JSRB), the Mintuo River Basin (MTRB), the Jialing River Basin (JLRB), the Wujiang River Basin (WJRB) and the mainstream region (MSB). The average annual runoff ranges from 297.5 to 642.1 mm. The average annual precipitation ranges from 723.4 to 1,133.9 mm. The average annual temperature ranges from 8.6 to 16.8 °C.

Meteorological data from 80 National Meteorological Observatory stations within the UYRB are collected from the National Meteorological Information Centre of China, including daily observations of precipitation (\( P \), mm), air

![Figure 1](image-url)
temperature (\(T, ^\circ\text{C}\)), relative humidity (\(\text{RH}, \%\)), wind speed (\(\text{WS}, \text{m s}^{-1}\)), and sunshine duration (\(\text{SD}, \text{h}\)) for the period from 1951 to 2020. The data have been subjected to strict quality control and inspection. Locations of the stations are shown in Figure 1. These stations are well distributed within the UYRB, which reflect the basin’s climatic characteristics. Among these stations, 10 have well-recorded radiation observations and are used to calibrate the Angstrom coefficients for estimating the solar radiation in the Penman–Montieth method. More detailed information on these meteorological stations is listed in Table 1. The missing data (accounting for 0.6% of the total data) are interpolated by the average meteorological data from three neighboring stations.

**METHODS**

**Penman–Montieth method**

As mentioned in the ‘Introduction’ section, \(\text{ET}_0\) is a theoretical climatic parameter, which reflects the evapotranspiration capacity of a basin under specific climatic conditions. Therefore, \(\text{ET}_0\) change and the causes provide evidence of current climate change occurring and historic trends. There are a multitude of methods for the estimation of \(\text{ET}_0\) (Xu & Singh 2002). Some of these methods are accurate and reliable; others provide only a rough approximation. Most of the methods were developed for use in specific studies and are most appropriate for use in climates similar to where they were developed (Xu et al. 2006). The Penman–Montieth method is considered to be the most reliable one among the \(\text{ET}_0\) estimation methods, because it integrates both aerodynamic and physiological parameters (Xu et al. 2006). \(\text{ET}_0\) is calculated by:

\[
\text{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}
\]  

where \(R_n\) is the net radiation at the crop surface (MJ m\(^{-2}\) d\(^{-1}\)), \(G\) is the soil heat flux density (MJ m\(^{-2}\) d\(^{-1}\)), \(\gamma\) is the psychrometric constant (kPa \(^{\circ}\text{C}^{-1}\)), \(T\) is the daily air temperature (\(^{\circ}\text{C}\)), \(u_2\) is the daily wind speed at 2 m above ground (m s\(^{-1}\)), \(e_s\) is the saturation vapor pressure (kPa), \(e_a\) is the actual vapor pressure (kPa), \(\Delta\) is the slope of the saturated vapor pressure in relation to air temperature (kPa \(^{\circ}\text{C}^{-1}\)).

The solar radiation is calculated using the Angstrom formula (Maroufpoor et al. 2020), which has been proven to be suitable for daily global radiation estimation in China (Chen et al. 2004).

\[
R_s = \left( a_s + b_s \frac{n}{N} \right) R_a
\]  

where \(R_s\) is the shortwave radiation (MJ m\(^{-2}\) d\(^{-1}\)), \(R_a\) is the extraterrestrial radiation (MJ m\(^{-2}\) d\(^{-1}\)), \(n\) is the actual duration of sunshine (h), \(N\) is the possible maximum duration of sunshine (h), \(a_s\) and \(b_s\) are two regression coefficients.

Differing from the previous studies which use the average value of coefficients \(a_s\) and \(b_s\) in the whole of China (Liu et al. 2010), we estimate the Angstrom coefficients using the measured radiation within the UYRB to ensure more accuracy and reliability. First, we use the formula given by the Penman–Montieth method to calculate the \(N\) and \(R_a\) based on date and latitude at 10 meteorological stations with radiation observation (see Figure 1 and Table 2). Secondly, we use nonlinear least-squares data fitting to estimate the \(a_s\) and \(b_s\) based on the observations of \(R_s\) and \(n\). Thirdly, we use the Kriging interpolation method (Xu et al. 2006) to obtain \(a_s\) and \(b_s\) of those stations with no radiation observation.

**Trend analysis method**

The nonparametric Mann-Kendall (MK) test is highly recommended to analyze monotonic trends of hydro-meteorological time series by the World Meteorological Organization (Zhang et al. 2018). In this study, it is used to identify temporal trends in \(\text{ET}_0\) and other climatic variables. For a time series \(X = \{x_1, x_2, \ldots, x_n\}\), the test statistic variable \(S\) is computed by:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k)
\]  

where \(n\) is the length (sample size) of the time series. We assume that the time-series data are independent and randomly distributed.
When the length of the time series is greater than 10, the normalized variable of $S$ is given by:

$$Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{Var}(S)}} & S > 0 \\
0 & S = 0 \\
\frac{S + 1}{\sqrt{\text{Var}(S)}} & S < 0 
\end{cases}$$

(4)
when \( Z < 0 \), the time series is identified as an upward trend. When \( Z > 0 \), the time series is identified as a downward trend. When \( |Z| \geq Z_{a}/2 \), the monotonic trend is believed to be significant at the significance level of \( \alpha \).

**Attribution analysis method**

To explore the causes of \( E_{T0} \) change, an attribution analysis method (Figure 2) is proposed in this study as follows: (1) The abrupt change points in climatic variable series are detected by using the time-series analysis method. (2) The climatic variable series are reconstructed based on the abrupt change analysis results to obtain stationary series. (3) \( E_{T0} \) is recalculated by using the reconstructed series for one climatic variable, while original data for other variables are retained. The difference between the recalculated \( E_{T0} \) and original \( E_{T0} \) is considered as the contribution of this climatic variable to \( E_{T0} \) change.

**Abrupt change analysis**

The nonparametric Pettitt test (Pettitt 1979) is employed in this study. The abrupt change point of the climatic variable series is detected by the Pettitt test, which judges whether there is a significant difference in the cumulative distribution function before and after the point. For the climatic variable series \( X = \{x_1, x_2, \ldots, x_n\} \), the Mann–Whitney statistic variable is calculated to test whether the samples \( x_1, x_2, \ldots, x_t \) and \( x_{t+1}, x_{t+2}, \ldots, x_n \) belong to the same population. The Mann–Whitney statistic variable \( U_{t,n} \) (Zhang et al. 2018) is given by:

\[
U_{t,n} = U_{1-t,n} + \sum_{j=1}^{n} \text{sgn}(x_i - x_j)
\]  

(5)

where \( t = 2, \ldots, n \). The point, which has the maximum \( U_{t,n} \) value, can be considered as the change. The significance of the change point can be tested by:

\[
P = 2 \exp \left\{-6(k_n)^2/(n^3 + n^2)\right\}
\]

(6)

where \( P \) denotes the significance of change point, and \( k_n \) denotes the maximum \( U_{t,n} \) value.

**Reconstruction of climatic variables series**

When there is a significant abrupt change point in a climatic variable series, the subseries before the abrupt change point is defined as the baseline series. The subseries after this abrupt change point is defined as the altered series. We replace the original data with the detrended data to obtain the reconstructed series. For the climatic variable series \( X = \{x_1, x_2, \ldots, x_n\} \), after the trend and slope being analyzed by using the MK test, the reconstructed climatic variable series is given by:

\[
x_b' = x_b - k_1(b-1)\Delta t
\]

(7)

\[
x_y' = x_y - k_2(y-a)\Delta t - \Delta a_1
\]

(8)

where \( a \) (1 < \( a < n \)) is the significant abrupt change point (year); \( b = 1, \ldots, a; \) \( x_b \) is the original value at time \( b \) (year); \( x_b' \) is the detrended value (mm); \( k_1 \) is the slope during baseline period (mm/year); \( y = a + 1, \ldots, n \) (year); \( x_y \) (mm) is the original value at time \( y; \) \( x_y' \) is the detrended value (mm); \( k_2 \) is slope during altered period (mm/year); \( \Delta t \) is the time step (year); \( \Delta a_1 \) is the difference between original value at time \( a \) and time 1 (year).
When there is not a significant abrupt change point in the climatic variable series, it suggests that no abrupt change has occurred or the abrupt point occurred before the study period. We replace the original data during the entire study period with the detrended data to obtain the reconstructed series. After the trend and slope being analyzed, the reconstructed climatic variable series is given by:

$$x'_z = x_z - k_3(z - 1)\Delta t$$  \hspace{1cm} (9)

where $z = 1, \ldots, n$, $x_z$ is the original value at time $z$ (year); $x'_z$ is the detrended value (mm); $k_3$ is the slope during the entire study period (mm/year).

**Contribution of climatic variable to ET₀ change**

ET₀ is regarded as a function of related climatic variables (e.g., $T$, RH, WS, and SD), which is described by the Penman–Montieth method. The ET₀ is written as:

$$ET₀ = F(X_1, X_2, \ldots, X_j, \ldots, X_m)$$  \hspace{1cm} (10)

where $F(\cdot)$ is the function of the Penman–Montieth method; $X_1, X_2, \ldots, X_j, \ldots, X_m$ are the related climatic variables. Then, the contribution of climatic variable $X_j$ to ET₀ change is calculated by:

$$C_j = F(X_1, X_2, \ldots, X_j, \ldots, X_m)$$

$$- F(X_1, X_2, \ldots, X'_j, \ldots, X_m)$$  \hspace{1cm} (11)

where $C_j$ is the contribution series of climatic variable $X_j$ to ET₀ change; $X'_j$ is the reconstructed series of climatic variable $X_j$. We use the slope value of the contribution series to represent the contribution of climatic variable to ET₀ change.

**Sensitivity analysis method**

Besides the change amount of climate variables, the sensitivity of ET₀ to climate variables has an important influence on ET₀ change. A small change in sensitive climatic factor may result in a great change in ET₀. To better understand the attribution results, the sensitivity analysis of ET₀ to climate variables is performed. A simple and widely used method is to compute and plot the relative changes of an input variable against the resultant relative change of the output variable as a curve, from which the sensitivities are easily read and compared (Liu et al. 2020; Zhang et al. 2020; Wang et al. 2021).

**RESULTS**

**Spatial distributions of annual ET₀ and related climatic variables**

Daily ET₀ is calculated by using the Penman–Montieth method at the 80 stations. Annual ET₀ is further calculated by accumulating the daily values. We plot the spatial distribution of mean annual ET₀ as shown in Figure 3. The annual ET₀ of the UYRB has an inhomogeneous spatial pattern with low values in the eastern part of the basin, high values in the western part, and very high values in the south-western part. The spatial distributions of the annual values of four related meteorological variables (i.e., SD, $T$, RH, and WS) are plotted in Figure 4. We find SD values in the western part of the UYRB, which are obviously larger than those in the eastern part. There is a distinct boundary between the western and eastern parts. From low to high value, a clear northwestern-southeastern gradient is found in the spatial distributions of $T$ and RH. Differing from the other climatic variables, the spatial distribution of WS is

![Figure 3](http://iwaponline.com/jwcc/article-pdf/12/6/2624/935148/jwc0122624.pdf)
relatively homogeneous except for a few isolated stations having high values. The integrated views of Figures 3 and 4 show the combined effects of SD, $T$, RH, and WS on ET$_0$. It can be seen that the highest ET$_0$ values occur in the southwestern part, where the SD value and $T$ value are very high. Meanwhile, the lowest ET$_0$ values found in the central region (southeast of the MTRB, south of JLRB, middle of the MSB) are the lowest, where the lowest SD, high $T$ values and low WS values are observed. In general, the spatial pattern of ET$_0$ in the UYRB is mainly due to the very high SD, very low RH, and high WS in the west, and the very low SD, very high RH, and low WS in the east.

**ET$_0$ trend**

The trends for the annual ET$_0$ during 1951–2020 are tested by using the MK test and plotted in Figure 5. The red upward triangles represent positive trends, and the blue downward triangles represent negative trends. Sizes of triangles indicate the magnitudes of change slopes. Solid triangles indicate significant trends with confidence level
higher than 95% (Zhang et al. 2018). It can be seen that the change of $ET_0$ has complex spatial variability in the UYRB. There are 55 stations presenting increasing trends in annual $ET_0$ (i.e., 69% of all stations), of which 38 stations (i.e., 48% of all stations) are statistically significant at 95% confidence level. Decreasing trends are detected in 25 stations (i.e., 31% of all stations), of which 10 stations (i.e., 12.5% of all stations) are dominated by significant negative trends at 95% confidence level. Annual $ET_0$ of the UYRB shows an upward trend in general. The significant increases of annual $ET_0$ gather in the central region of the UYRB, where the mean annual $ET_0$ is low. The stations showing negative trends mainly distribute in the upper Yalong River, lower Jinsha River, upper Jiangling River, and Middle Minjiang River.

Trends of the area-averaged $ET_0$ in the UYRB and the subbasins are also analyzed by using the MK test. The results are summarized in Table 3. The area-averaged $ET_0$ of the UYRB has a significant increasing trend at confidence level of 95%, with a slope of 3.3 mm/year. $ET_0$ in the JSRB, MTRB, JLBR, WJRB, and MSB all show increasing trends, with slopes of 2.9, 2.9, 3.9, 3.0, and 4.9 mm/year, respectively. The results are consistent in the subbasins except that the confidence level is lower than 95%.

**Climate factors for $ET_0$ change**

Trends of SD, $T$, RH, and WS are also analyzed to understand the causal mechanism behind the changes of $ET_0$. The results of trend analysis for annual climatic variables and their spatial patterns are shown in Figures 6. Beginning with the annual $T$, it can be seen that obvious warming trends have occurred across the entire UYRB. This is consistent with global warming reported in most parts of the world. There are 70 stations presenting positive trends in annual $T$ (i.e., 87.5% of all stations), among which 61 stations (i.e., 76% of all stations) are statistically significant at 95% confidence level. The largest increasing trends (greater than 0.04 °C/year) mainly distribute in the western part of the UYRB, while smaller positive trends (around or less than 0.03 °C/year) occur in the eastern part. Contrarily, although increasing trends are observed in a few stations distributed in the western part, the annual SD of the UYRB shows an upward trend in general. Sixty-five stations (i.e., 81% of all stations) present decreasing trends, with most trends being greater than 4 h/year. Among these stations, decreases in 47 stations (i.e., 59% of all stations) are statistically significant. Similar changes are detected in the annual RH. Fifty-nine stations (i.e., 74% of all stations) show decreasing trends, and half of them are statistically significant. The annual RH has the least number of statistically significant trends. There are 26 stations having significant negative trends and 7 stations having significant positive trends. The annual WS shows mixed increasing and decreasing trends in the entire UYRB, which does not have an obvious trend pattern. There are 54 stations (i.e., 67.5% of all stations) showing decreasing trends, and most of them are statistically significant.

**Contributions to $ET_0$ trend**

The proposed attribution analysis method is employed for the UYRB and all subbasins to evaluate the effects of changes of climatic variables on $ET_0$. Abrupt change analysis is first done for area-averaged climatic variable series in the UYRB and each subbasin. The abrupt change points and corresponding confidence levels are listed in Table 4. In this study, the abrupt change points at the confidence level of 95% or more are considered as significant. The $T$ series, RH series, and WS series can be divided into subseries by the abrupt change points. We then do the Pettitt test on the subseries. The results show that there are no significant abrupt change points in the subseries, indicating the absence of multiple change points in the climatic variable series. Then, following the steps of the proposed method, the climatic variable series are reconstructed according to the abrupt change analysis results,
and contributions to ET₀ change are calculated. The contributions of climatic variables to ET₀ change are shown in Figure 7. It can be found that ET₀ change results from the combined effect of the climatic variables and the contributions vary in different subbasins. For the five subbasins and entire UYRB, RH has the dominant influence on ET₀ change. RH decrease tends to increase ET₀, causing 3.29, 3.24, 5.51, 4.36, and 5.51 mm/year of ET₀ increase in the JSRB, MTRB, JLRB, WJRB, and MSB, respectively. The

![Figure 6](image1.png)

**Figure 6** | Annual trend slopes and the MK test result (at the 95% confidence level) of climatic variables during 1951–2020: (a) sunshine duration, (b) air temperature, (c) relative humidity, and (d) wind speed.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Abrupt change point (confidence level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>T</td>
</tr>
<tr>
<td>UYRB</td>
<td>1988 (–)</td>
</tr>
<tr>
<td>JSRB</td>
<td>1988 (–)</td>
</tr>
<tr>
<td>MTRB</td>
<td>1988 (–)</td>
</tr>
<tr>
<td>JLRB</td>
<td>1996 (–)</td>
</tr>
<tr>
<td>WJRB</td>
<td>1993 (–)</td>
</tr>
<tr>
<td>MSB</td>
<td>1997 (–)</td>
</tr>
</tbody>
</table>

**Table 4** | Abrupt change points of climatic variable series in the UYRB and subbasins

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>SD</th>
<th>T</th>
<th>RH</th>
<th>WS</th>
</tr>
</thead>
</table>

Note: ‘–’ represents a confidence level lower than 95%.

![Figure 7](image2.png)

**Figure 7** | Contributions of climatic variables to ET₀ change in the UYRB and subbasins.
decreasing SD contributes to decrease ET\textsubscript{0} in the subbasins and entire UYRB. SD takes the second place of contributions of climatic variables to ET\textsubscript{0} change in MTRB, JLRB, WJRB, and the entire UYRB. Impacts of SD on ET\textsubscript{0} in the eastern part of UYRB are more evident in the western part. The increasing \( T \) is mainly responsible for the increasing trends in ET\textsubscript{0} in the UYRB. Impacts of \( T \) on ET\textsubscript{0} are more evident in the JSRB, where \( T \) is the second dominant factor. WS has the least contribution among selected climatic variables in the UYRB. The influence of WS is more complex than others in space. Changes in WS contribute to decrease ET\textsubscript{0} in the subbasins and entire UYRB except the JLRB, where WS tends to increase ET\textsubscript{0}.

**Sensitivity of the ET\textsubscript{0} to climatic variables**

\( T \) has a significant trend in the UYRB but takes the third place in terms of contribution to ET\textsubscript{0} change. Therefore, sensitivity analysis is conducted by using the sensitivity curve method to further explore the causes of ET\textsubscript{0} change. Scenarios with \( X_{j} + 0\% \) of \( X_{j} \), \( X_{j} \pm 10\% \) of \( X_{j} \), \( X_{j} \pm 20\% \) of \( X_{j} \), and \( X_{j} \pm 30\% \) of \( X_{j} \) are generated for the climatic variables and used as the input for the Penman–Montieth method. The corresponding relative changes of ET\textsubscript{0} against the relative changes of climate variables in the UYRB and subbasins are plotted in Figure 8. At the same relative change value of climate variable, the larger corresponding relative change of ET\textsubscript{0} means the stronger sensitivity of the ET\textsubscript{0} to climate variable. It can be seen that the sensitivities vary in climate variables and space, but the general law is consistent. Positive correlations are identified between relative change of ET\textsubscript{0} and relative change of SD, \( T \) and WS in the UYRB and subbasins, while negative correlations are identified between relative change of ET\textsubscript{0} and relative change of RH. This means RH decrease and \( T \) increase tend to increase ET\textsubscript{0}, while SD decrease and WS decrease tend to decrease ET\textsubscript{0}. The results of sensitivity analysis are in accordance with the results of attribution analysis. In the entire UYRB and subbasins, relative change from \(-30\%\) to \(-50\%\) in SD, \( T \), RH, and WS can result in relative change from \(-8\%\) to \(-7\%\), \(-3\%\) to \(-2\%\), \(-14\%\) to \(-15\%\), and \(-7\%\) to \(-4\%\) in ET\textsubscript{0}. RH is the most sensitive factor although the sensitivity degree varies in different subbasins. This is consistent with results of previous studies conducted in the Yangtze River Basin (Gong et al. 2006; Xu et al. 2006) and in all climate regions of China (Yin et al. 2010). The impacts of climatic variables on ET\textsubscript{0} depend not only on their change slopes but also the sensitivities. The sensitivity of ET\textsubscript{0} to \( T \) is the lowest in the entire UYRB and subbasins. Therefore, it is easy to explain why \( T \) variables present larger change slopes but provide small contribution in ET\textsubscript{0} increase.

![Figure 8](http://iwaponline.com/jwcc/article-pdf/12/6/2624/935148/jwc0122624.pdf)

**Figure 8** | Sensitivity of ET\textsubscript{0} to climatic variables in the UYRB and subbasins.
DISCUSSION

In this study, the series reconstruction method for climatic variable is different from the previous studies (Xu et al. 2006; Wang et al. 2022). As mentioned in the ‘Introduction’ section, the traditional recovered stationary series method used in previous studies reconstruct the climatic variable series by the trend and slope of the whole series, without considering whether there is an abrupt change point. In fact, when there is an abrupt change point in one climatic variable series, the subseries before and after abrupt change point commonly have different trends and slopes. In this case, the traditional recovered stationary series method will misestimate the changes in variable series. What’s worse, in most cases, subseries before abrupt change point is flatter, and the traditional method will mean this subseries has an opposite trend to the actual situation. We use the example of the $T$ in MTRB for illustration (Figure 9). An abrupt change has been detected in the year 1997 (Table 4). It can be seen from Figure 9(a) that the original $T$ series has an upward trend with a slope of 0.0151 °C/year. Two subseries also show upward trends. Slopes of the two series are 0.0009 and 0.0157 °C/year. The subseries (1951–1997) is flatter than the subseries (1998–2020). We reconstruct the original $T$ series using the traditional recovered stationary series method, as shown in Figure 9(b). It can be seen that the reconstructed subseries (1951–1997) shows a decreasing trend, which is contrary to the actual situation. Results of the improved method are shown in Figure 9(c). It can be seen that the original $T$ series is better detrended. Both subseries recover stationary. The study period in this work is much longer than the studies mentioned above, using the proposed series reconstruction method obtains more reliable results. It is worth noting that this proposed method is also applicable when there are multiple change points. When there are $N$ significant abrupt change points in the original series, we divide the original series into $N + 1$ subseries and reconstruct each subseries using the proposed method. In addition, other forcings than the studied ones (i.e., RH, $T$, SD, and $S$)
WS) are not considered in the proposed method. This restriction is justified but is possible to overestimate the contributions of RH, T, SD, and WS.

**CONCLUSIONS**

In this study, we estimate the ET₀ in 80 meteorological observatory stations within the UYRB during 1951–2020 by using the Penman–Monteith method. The spatial distributions of ET₀ and ET₀ trend are studied to describe the spatial characteristics of ET₀ change. Trends of the area-averaged ET₀ in the subbasins and entire UYRB are also analyzed to describe the temporal characteristics. An attribution analysis method is proposed to quantify the impacts of changes in climatic variables on ET₀. The sensitivity analysis is conducted to further explore the causes of ET₀ change.

The UYRB has an irreplaceable position and inestimable value in China’s strategic reserve of water resources and hydropower resources, which is vulnerable and sensitive to changing environment. This study aims to provide a newer and more detailed description of ET₀ change at basin and subbasin scales in the UYRB, which provides evidence of current climate change occurring and historic trends. Special efforts are also made in the attribution of ET₀ change, which offers guidance on adaptive regulation of water resources systems under climate change.

Several important findings are revealed in the UYRB. During 1951–2020, ET₀ increases significantly by 3.3 mm/year in the entire UYRB. Stations with significant increases in annual ET₀ are concentrated in the central part of the UYRB, where the mean annual ET₀ is low. The stations showing negative trends are mainly distributed in the upper Yalong River, lower Jinsha River, upper Jiangling River, and middle Minjiang River. Relative humidity has the dominant influence on ET₀ change. Relative humidity decrease tends to increase ET₀, causing 4.69 mm/year of ET₀ increase in the entire UYRB. Temperature increase tends to increase ET₀, while sunshine duration decrease and wind speed decrease contribute to decrease ET₀ in the UYRB. Contributions of climatic variables to ET₀ change vary in subbasins.

Seasonal patterns of ET₀ changes and their causes have not been analyzed in this work. Seasonal trends in ET₀ are possible to have a great impact on water resources planning and management due to seasonal behaviors of water resources allocation such as irrigation. Therefore, we are doing another detailed study on seasonal ET₀ changes and their impacts as a follow-up study to this paper.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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