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50-year evapotranspiration declining and potential causations in subtropical Guangdong province, southern China

Xiuzhi Chen [a], Xiaodong Liu [a,b,1], Guoyi Zhou [a,*], Liusheng Han [c], Wei Liu [b,c,d,e], Jishan Liao [f]

[a] Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[b] University of Chinese Academy of Sciences, Bejing 10094, China
[c] Guangzhou Institute of Geography, Guangzhou 510070, China
[d] Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[e] Guangdong Climate Center, Guangzhou 510080, China
[f] Department of Biological Sciences, University of Notre Dame, Notre Dame, IN 46556 USA

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ABSTRACT

Background: Evapotranspiration (ET) is an important flux term in the terrestrial hydrologic cycle system that integrated atmospheric and land surfaces, hydrological and biological processes. Any variations of the hydrological processes induced by climate change and forest management would be significantly reflected in ET component.
Methods: In this paper, we firstly calculated Guangdong's 50-year annual, humid- and dry-season ET jointly based on the water balance model and a physical-based ET model. Then, the separate contributions of climate change and reforestation on ET changes were evaluated by the double mass curve method.
Results: The time-series annual ET declined significantly ($p < 0.001$) during the past 50 years. The year 1980 showed to be an important change point. Both humid- and dry-season ET kept much stable during the former period 1956–1979, while decreased significantly ($p < 0.001$) during the later period 1980–2006. Climate change and reforestation contributed for about −34.02 and 31.03 mm/year for the annual ET variations, while about −28.18 and 27.25 mm/year for the dry seasons, and about −5.84 and 3.78 mm/year for the humid seasons, respectively.
Discussions and conclusions: By comparison, the positive contributions of reforestation on ET changes were completely offset by the negative contributions of climate changes. Climate changes were the key factors responsible for the reduction of Guangdong's ET. In particular, the regional ET in dry seasons was quite more sensitive to climate change and land cover changes, while much less sensitive in humid seasons. Our results also confirmed that land cover changes would have little impacts on the regional ET changes when $P/PET > 1$, but might cause greatly influences on ET when $P/PET < 1$. These conclusions indicate that afforestation might be actively encouraged in humid regions, but should be treated cautiously in non-humid regions or even be limited in arid regions. It will be directly useful for guiding government in future forest management.

1. Introduction

Recently, great emphasis has been given to two focuses in the fields of hydrology researches: (1) responses of hydrological processes to climate change (Bonell, 1998; Huntington, 2003; Neff et al., 2000; Shrestha et al., 2012) and (2) relations between hydrological processes and forest management (Legesse et al., 2003; Lu et al., 2013; Mango et al., 2011; Sun et al., 2006). The effects of climate change and forest management on hydrological processes are being pursued vigorously as a multi-disciplinary problem (Goyal, 2004). Nevertheless, the hydrologic responses to reforestation and deforestation are not well cognized at present (Sun et al., 2006). It has become the most important and controversial topic in the forest hydrology community (Lin and Wei, 2008; McVicar, 2007; Scott and Prinsloo, 2008). The general conclusion believed that forest removal or harvesting could increase surface runoff, while reforestation caused its reduction (Bradshaw et al., 2007; Bruijnzeel, 2004; Jackson et al., 2005; Oudin et al., 2008). But, some other results suggested limited or even no response (Antonio et al., 2008; Buttle and Metcalfe, 2000; Dyhr-Nielsen, 1986; Wilk et al., 2001), which was contrary to the traditional hypothesis. The inconsistent opinion about the relations between forest management and hydrological processes was found not only in small-scale watershed studies (Bruijnzeel, 2004; Jackson et al., 2005; Liu and Zhong, 1978; Ma, 1987), but also in large-scale watershed studies (Zhou et al., 2010).

Evapotranspiration component (ET), which consumes nearly 60–75% of precipitation inputs, is an important flux term in the terrestrial

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* Corresponding author.
E-mail addresses: chenxz@scbg.ac.cn (X. Chen), gyzhou@scib.ac.cn (G. Zhou).
[1] Co-first author.

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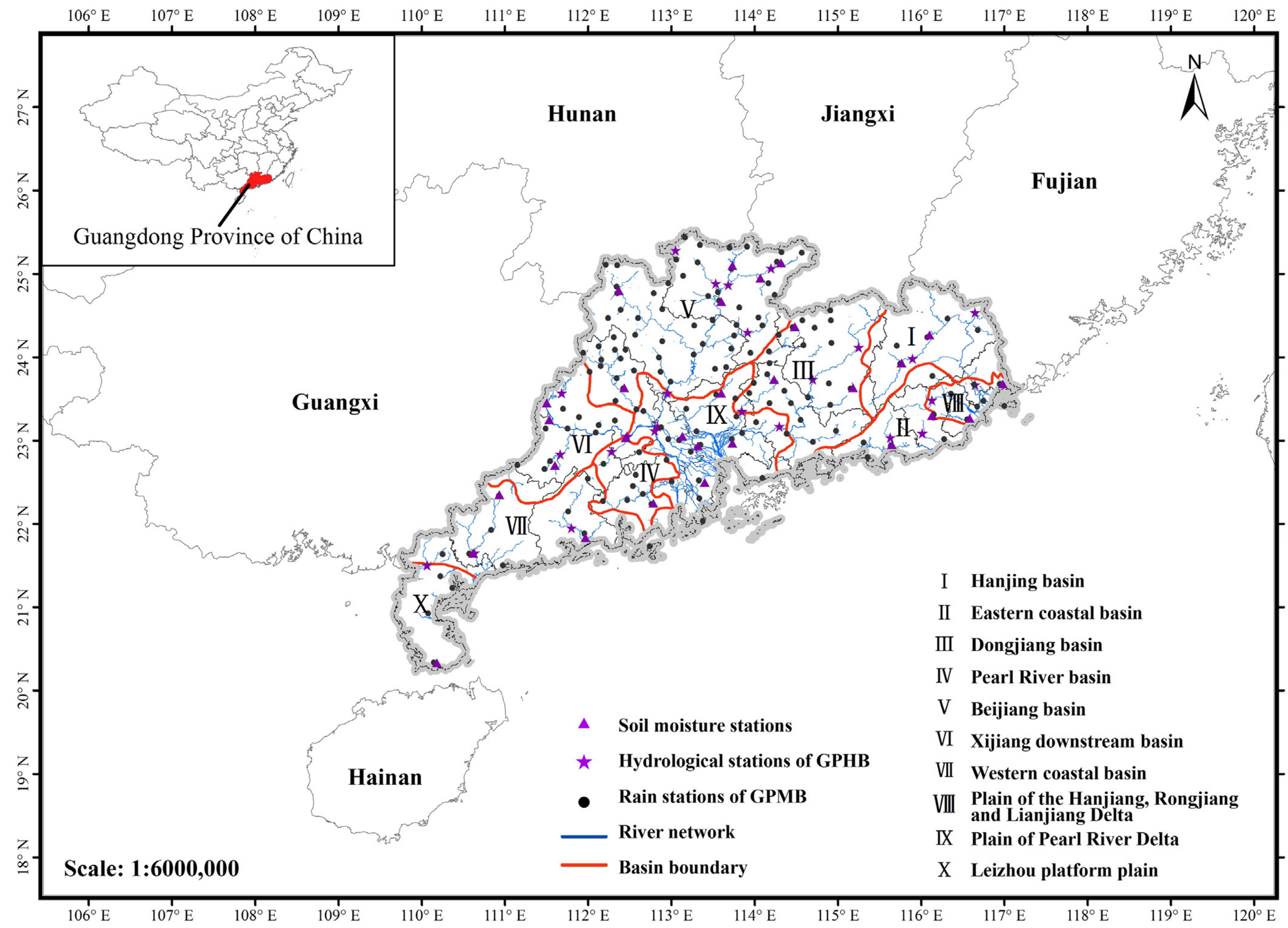

Fig. 1. Study area and observation stations.

hydrologic cycle system that integrated atmospheric and land surfaces, hydrology and biological processes (Chattopadhyay and Hulme, 1997; Penman, 1948). It is an effective indicator in describing regional hydrological system (Currie, 1991; Huo et al., 2013; Law et al., 2002; Zhou et al., 2008a, 2008b). Any variations of the hydrological processes induced by climate change and forest management will be significantly reflected in ET component (Bultot et al., 1988; Gleick, 1986; Goyal, 2004; Hillel, 1998; Huo et al., 2013; Zhang and Schilling, 2006). Hence, quantifying the regional-scale time-series ET is vital for understanding the interaction mechanizations between forest management and hydrological processes.

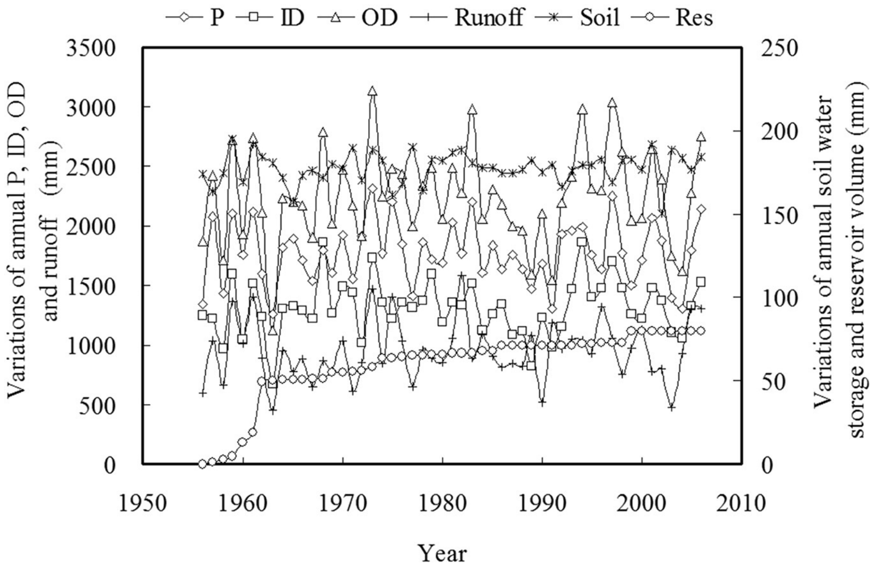

Fig. 2. Annual variations of the hydrological component.

Table 1
The natural water supplements of groundwater (mm) during the decades of 1970s, 1980s and 1990s, respectively (Zhang and Li, 2004).

Basins	Natural water supply for groundwater (mm)		
	1970s	1980s	1990s
Hanjing basin	406.27	423.09	409.51
The eastern coastal basin	520.37	522.36	537.26
Dongjiang basin	407.79	435.72	429.33
The Pearl River Basin	357.90	354.47	354.93
Beijiang basin	388.59	373.27	392.76
Xijiang downstream basin	348.42	341.53	336.04
The western coastal basin	367.47	358.63	368.99
Plain of the Hanjiang, Rongjiang and Lianjiang Delta	381.64	392.15	399.02
Plain of the Pearl River Delta	260.45	255.46	257.63
Leizhou platform plain	805.43	799.42	770.41
Total annual average	407.44	406.97	410.36

Our recent theoretical analyses from global watershed studies proved that land cover changes in non-humid regions might lead to greater hydrological responses, but tend to cause smaller hydrological responses in humid regions (Zhou et al., 2015). Here, we assume that the hypothesis still hold for large-scale unclosed regions as well as the small-scale watersheds. For this purpose, we select the subtropical Guangdong province of southern China as the study area. During the past century, Guangdong has experienced a long-term reforestation, along with obvious climate change process (Yang et al., 2011). In addition, there are obvious wet and dry seasons (Zhou et al., 2010). About 1384 mm (78%) and 386 mm (22%) precipitation fall in the wet and dry seasons, respectively. So, Guangdong would be regarded as the humid region in wet seasons, but as the non-humid region in dry seasons. Therefore, monitoring its humid- and dry-season ET trends and quantifying the separate contributions of climate change and reforestation would be important to understand the relations between forest, climate change and hydrology. The overall goals of this study are to quantify the 50-year humid- and dry-season ET component of Guangdong province based on the water balance model (WBM) and Fu's ET model and then to calculate the separate contributions of climate change and reforestation on influencing the trends of Guangdong's humid- and dry-season ET.

2. Materials and methods

2.1. Study area

Guangdong province, with an area of 179,752 km^2, is located in the humid southern China. The climate here is the tropical and subtropical monsoon. The annual mean temperature is 22 °C. Annual precipitation amount is about 1770 mm. According to the historical monthly rainfalls of Guangdong province, 12 months can be classified into humid seasons (April to September) and dry seasons (October to March) (Zhou et al., 2010). The tropical and subtropical broad-leaved evergreen forests are the major climax forest communities. The sclerophyllous evergreen savanna shrub and grassland are the major secondary forest communities. However, due to the interference and damage by humans, the original forest community structure has been damaged seriously. Currently, more than 68% are plantations, which are mainly Chinese fir, masson pine, eucalyptus, Casuarina and bamboo (Huang et al., 2002). In order to reduce the environmental problems, the Guangdong provincial government launched a large-scale, 10-year reforestation program in the 1980s. Through implementation of this program, the forest coverage rate of the province increased from 20.01–30.80% in 1956–1979 period to 27.20–56.90% in 1980–2006 period.

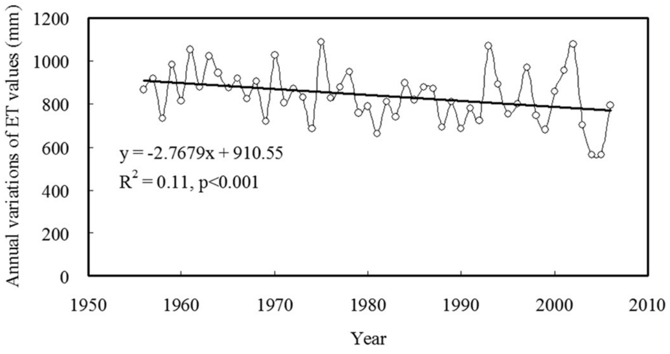

Fig. 3. 50-year annual ET estimated using the water balance model.

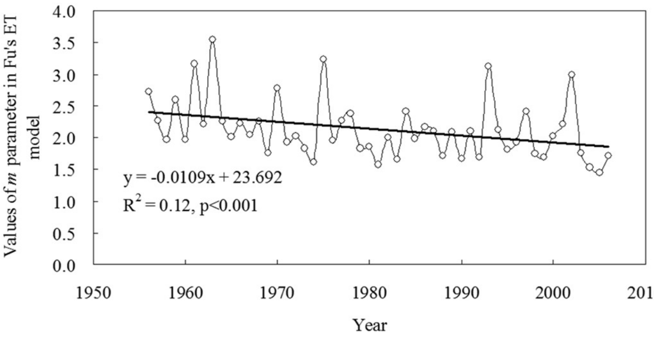

Fig. 4. Values of *m* parameter in Fu's ET model from 1956 to 2006.

In total, Guangdong is divided into 10 drainage basins (Fig. 1), e.g. Hanjiang basin, the eastern coastal basin, Dongjiang basin, the Pearl River Basin, Beijiang basin, Xijiang downstream basin, the western coastal basin, Plain of the Hanjiang, Rongjiang and Lianjiang Delta, Plain of the Pearl River Delta and Leizhou platform plain. They collect and carry the majority of Guangdong's river discharge and eventually flow into the South China Sea. There are 265 in-situ observation stations in total within Guangdong province for monitoring its hydrological variables and climate conditions. Among these stations, 179 belong to Guangdong Provincial Hydrological Bureau (GPHB), while the other 86 belong to Guangdong Provincial Meteorological Bureau (GPMB). There are also 26 observation stations, mainly located in forest, shrub and grass cover lands, for monitoring Guangdong's soil water storage conditions.

2.2. Water balance model (WBM) for quantifying the annual ET

The terrestrial component of hydrologic cycle was likewise expressed in four terms: precipitation, evapotranspiration, runoff and

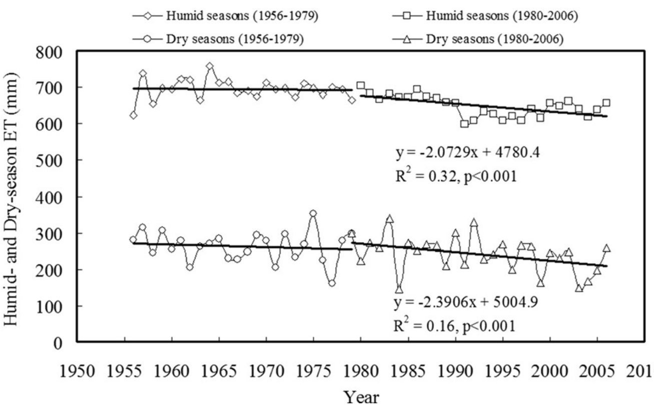

Fig. 5. Humid- and dry-season ET of Guangdong province from 1956 to 2006.

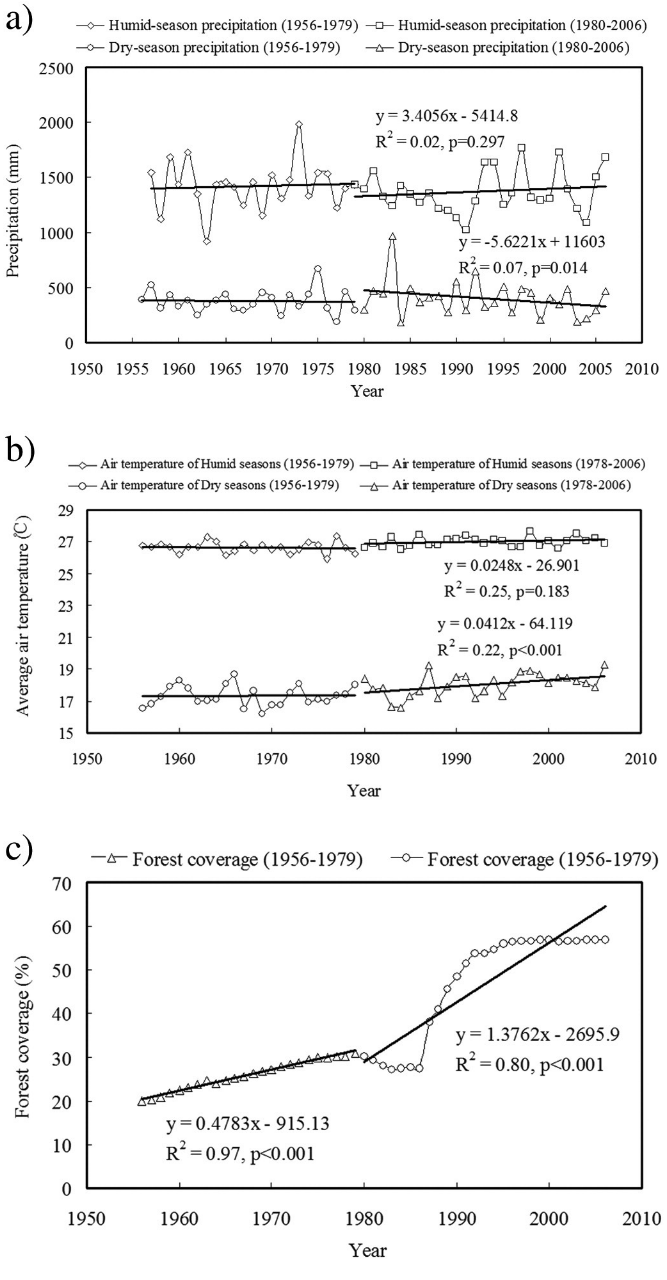

Fig. 6. Precipitation (a), air temperature (b) and forest coverage (c) from 1956 to 2006.

system water storage (Yeh et al., 1998; Rodell et al., 2004a, 2004b; Seneviratne et al., 2004; Moiwo et al., 2011a, 2011b). The annual water balance for a closed catchment or watershed could be expressed as following (Moiwo et al., 2011a, 2011b):

$$P = ET + Run + \Delta S \tag{1}$$

where *P* was the annual precipitation (mm), *Run* was the annual runoff (mm), *ET* was the annual evapotranspiration (mm), and ΔS was the value changes of system water storage between last year and this year (mm).

For a large-scale region (city, province or country), the system water storage should include the reservoir water, soil water storage and groundwater variations. What is more, the runoff of last year cannot flow all out of the region within the year. So, the runoff of last year should be considered as an initializing component of the system water storage for the next year. The inflow discharge from other regions and outflow discharge to other regions should also be included in the regional water balance. Hence, this paper expressed the WBM as:

$$P + ID = ET + OD + \Delta S \tag{2}$$

where *ID* was the annual inflow discharge from other regions (mm), *OD* was the annual outflow discharge to other regions or sea (mm), and ΔS was the variation of system water storage between the last year and this year (mm). ΔS included the annual variations of soil water storage ($\Delta Soil$), variations of river water storage (ΔRiv), variations of reservoir volume (ΔRes) and variations of ground water storage ($\Delta Ground$): $\Delta S = \Delta Soil + \Delta Riv + \Delta Res + \Delta Ground$.

Here, the water balance model at the annual temporal-scale for an unclosed region was improved as formula 3. We use this improved water balance model for quantifying the 50-year annual ET of Guangdong province.

$$P + ID = ET + OD + \Delta Soil + \Delta Riv + \Delta Res + \Delta Ground \tag{3}$$

2.3. Fu's ET model for quantifying the humid- and dry-season ET

A classic empirical model is represented by the formula of the single-line type (Budyko, 1958) that relates regional ET with several important driving variables such as precipitation, potential evapotranspiration (PET) and land topography (Donohue et al., 2007; Zhang et al., 2001, 2004). Zhang et al. (2004) proved that Fu's formula (Fu, 1981) (Eq. (4)), which is based on dimensional analysis theories, is the best model for estimating regional ET. We verified Fu's model with published data from globally time-trend studies (n = 1928) and paired-watershed experiential studies (n = 250), which contain forest, shrub, grassland, cropland and mixed land (Zhou et al., 2015). More than 90% of the time-trend data and 88% of the paired-watershed experiential data fit the Fu's theoretical model. Also, the watershed areas vary from 0.01 km^2 scale to more than 100,000 km^2 scale. Thus, this paper uses Fu's ET model to estimate Guangdong's humid- and dry-season ET.

$$ET = PET\left\{1 + \frac{P}{PET} - \left[1 + \left(\frac{P}{PET}\right)^{m}\right]^{1/m}\right\} \tag{4}$$

where *m* was a model parameter varying from 1 to infinity.

Table 2
Descriptions of precipitation, air temperature and forest coverage from 1956 to 2006.

Variables	Seasons	Period 1956–1979			Period 1980–2006		
		Range	Standard deviation	Linear significant	Range	Standard deviation	Linear significant
Precipitation (mm)	Humid seasons	916.77–1989.22	234.35	0.341	1023.52–1764.51	193.93	0.297
	Dry seasons	189.24–666.28	101.77	0.226	180.20–966.62	163.90	0.014
Air temperature (°C)	Humid seasons	25.94–27.35	0.34	0.391	26.55–27.68	0.30	0.183
	Dry seasons	16.21–18.66	0.63	0.188	16.61–19.27	0.70	0.000
Forest coverage (%)	–	20.01–30.80	3.41	0.000	27.20–56.90	12.35	0.000

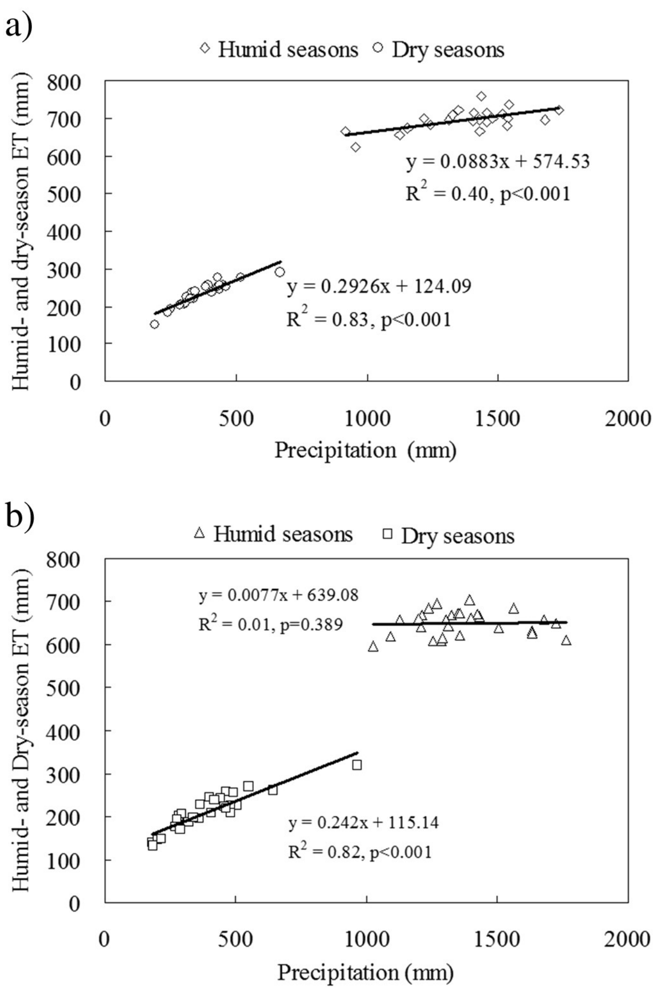

Fig. 7. Scatter diagrams between humid-season, dry-season ET and corresponding precipitation during 1956–1979 period (a) and 1980–2006 period (b), respectively.

2.4. Hamon's method for calculating the annual PET

Annual PET can be calculated by summarizing the monthly PET. Due to the large-scale coverage of our study area, some meteorological variables, e.g. wind speed and relative humidity, always vary greatly from north to south and from east to west. These might bring unexpected errors in predicting Guangdong's ET. It indicates that more variables considered in the PET model don't mean higher accuracies. As this paper mainly aims to study on the relative variations of Guangdong's time-series hydrological variables, so we use the simple Hamon's model (formula 5, Federer and Lash, 1978), which contains only air temperature and daytime length, to calculate the PET variable. Air temperature data can be obtained from the meteorological stations. Daytime length can be calculated using a function of latitude.

$$PET = 0.1651 \times D \times V_d \times k \tag{5}$$

where D is the time from sunrise to sunset in multiples of 12 h, computed as a function of date, latitude, slope, and aspect and V_d is the saturated vapor density ($g{*}m^{-3}$) at the daily mean temperature (T) (°C).

$$V_d = 216.7 \times V_s/(T + 273.3) \tag{6}$$

where V_s is the saturated vapor pressure (mb).

$$V_s = 6.108 \times \exp[17.26939 \times T/(T + 273.3)] \tag{7}$$

where k is the correction coefficient to adjust ET_0 that was calculated based on Hamon's method to measured values. Previous studies indicated that it was appropriate to use $k = 1.3$ to estimate forest ET_0 for the Coweeta (CW) site and $k = 1.2$ to estimate it for other sites (Zhou et al., 2008a, 2008b). As k is linearly correlated with PET, this paper calculates the time-series k values of Guangdong as follows: $k = Coverage \times 1.3 + (1 - Coverage) \times 1.2$, where *Coverage* means the forest coverage ratio.

2.5. Methods for calculating other hydrological components

The average annual precipitation (P) of Guangdong province is calculated on basis of the observed daily precipitation data from the 86 meteorological stations of GPMB. The average annual inflow discharge (ID), outflow discharge (OD) and annual water storage (ΔRiv) of Guangdong province are observed by the 179 stations of GPHB. The observed data are in unit of m^3. In this paper, we convert them into unit of mm by dividing the corresponding coverage areas (m^2). Similarly, the reservoir volume (ΔRes) in unit of mm is also calculated by dividing the total amounts of reservoir storage (in unit of m^3) by the reservoir area (in unit of m). The annual variations of soil water storage ($\Delta Soil$) are calculated by averaging the soil water storage data from the 26 observation stations.

The 50-year forest coverage data are provided by the Forest and Land Resources Bureaus of Guangdong province, with the error less than 1% (State Forestry Administration, 2006). Missing data in years of 1961–1962, 1965, 1967, 1972, 1974, 1976–1977, 1981–1982, and 1984 are estimated using a simple linear interpolation method. As Guangdong's forest coverage is on the whole much stable during these periods, we ignored the estimation error of missing forest coverage data (Zhou et al., 2010).

2.6. Method for quantifying the contributions of climate change and reforestation on ET

The double mass curve of cumulative hydrological variable, for example ET, against cumulative precipitation is proved to be effective in quantifying the impacts of climate change and other factors, for example reforestation, on the hydrological variable (Hinkley, 1971; Zhou et al., 2010). If there is a significant breakpoint in the double mass curve, it means that there are also other factors influencing the hydrological variable except for climate change. Contrarily, if there is no significant breakpoint in the double mass curve, it means that climate change is the only factor contributing to the variations of this hydrological variable.

Once there is a breakpoint, we developed a fitted line between the cumulative hydrological variable and cumulative precipitations on the

Table 3
Correlation analysis between time-series ET and precipitation during period 1956–1979 and 1980–2006, respectively.

Periods	Annual ET (mm)		Humid-season ET (mm)		Dry-season ET (mm)	
	Correlation value (R)	p value	Correlation value (R)	p value	Correlation value (R)	p value
1956–1979	0.79	0.000	0.63	0.019	0.91	0.000
1980–2006	0.61	0.000	0.10	0.397	0.91	0.000

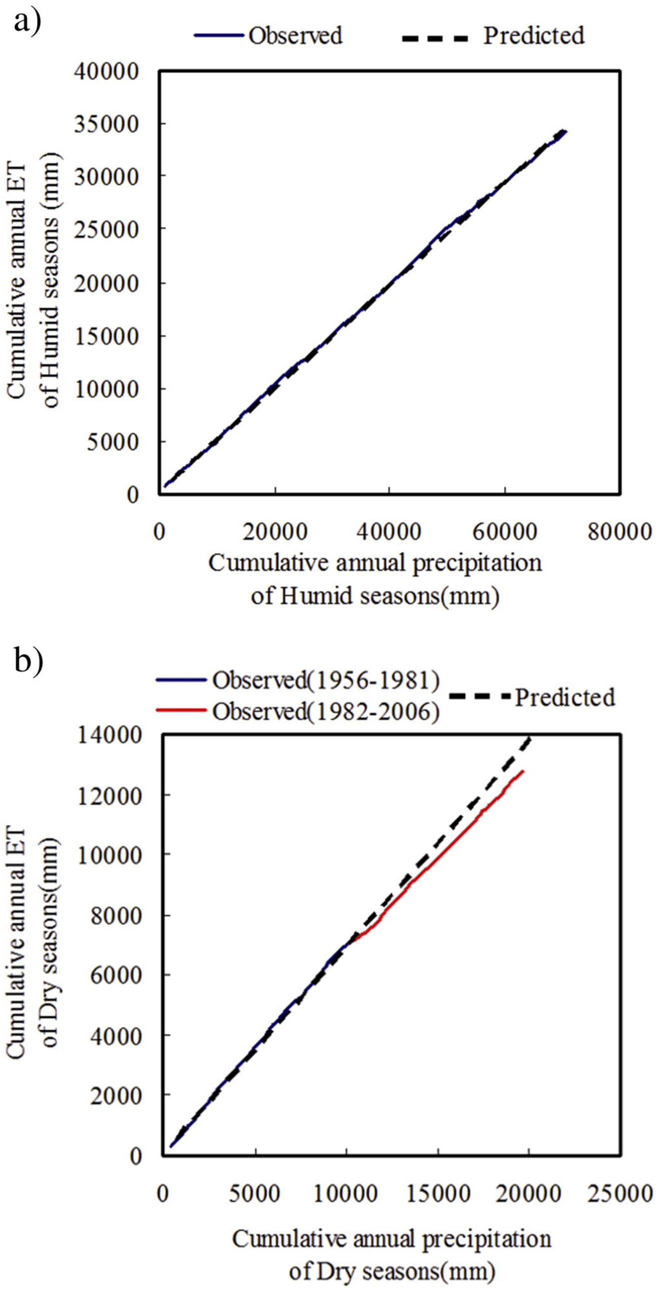

Fig. 8. Double mass curve between cumulative annual precipitation and cumulative annual ET in the humid seasons (a) and dry (b) seasons from 1956 to 2006.

basis of the data before the breakpoint. Then, the cumulative hydrological variable of years after the breakpoint was predicted based on the linear relationship. Next, the contribution values of reforestation were calculated as predicted hydrological variable minus corresponding observed hydrological variable. Finally, contributions of climate change were derived by deducting the effects of reforestation from the total variations of the hydrological variable.

2.7. Statistical analysis methods

Correlation analyses are conducted by the linear regression method. The trend significances (p-values) of the time-series data are calculated by the nonparametric Mann–Kendall test, which has been widely used to detect monotonic trends in environmental time series (Liu et al., 2011; Peng et al., 2014; Sheffield and Wood, 2008). We use the Fzero function of Matlab software to derive the time-series m values of Guangdong province based on Fu's ET model from the annual precipitation, PET and ET variables.

3. Results

3.1. Quantify the average annual, humid- and dry-season ET

The time-series annual precipitation, inflow discharge, outflow discharge, river runoff, and soil water storage are presented in Fig. 2. The 100 cm-depth soil water storage varied little during the past 50 years. The natural water supplements of groundwater in 10 major basins of Guangdong province, measured in China's Second Water Resource Survey (Zhang and Li, 2004), also changed little during the decades of 1970s, 1980s and 1990s (Table 1). So, the annual variations of soil water storage and groundwater component are ignored and set as zero in the paper. Then, the 50-year time-series annual ET of Guangdong province are estimated from the annual precipitation, inflow discharge, outflow discharge and annual variations of river water storage and reservoir volume. Results indicate that the average annual ET values of Guangdong province declined significantly ($p < 0.001$) during the past 50 years (Fig. 3).

After obtaining Guangdong's 50-year annual ET, the time-series values of m parameter in Fu's ET model of Guangdong province were derived and presented in Fig. 4. There is also a significant decrease trend from 1956 to 2006. The m parameter in Fu's ET model is influenced little by climate factors, such as precipitation and temperature, while it is only related to watershed characteristics, such as the fractional vegetation cover, catchment average slope, relative infiltration capacity, and the relative soil storage capacity (Zhou et al., 2015). Because most of vegetations in the subtropical Guangdong province are non-deciduous, we assume that m value varies little within one year. The 50-year humid- and dry-season ET of Guangdong province was then calculated respectively from the humid- and dry-season PET, precipitation and m values based on Fu's ET model. From 1956 to 1979, the average ET in both humid and dry seasons remained much stable. However, from 1980 to 2006 the average annual ET in both humid and dry seasons decreased obviously ($p < 0.001$).

3.2. The contributions of climate change and forestation on ET

Climate change (precipitation and air temperature) and land surface cover/use change are the two major factors impacting the regional ET (Fu, 1981; Zhang et al., 2004; Zhou et al., 2008a, 2008b). The variation trends of Guangdong's time-series precipitation, air temperature and forest coverage are presented in Fig. 6 and Table 2. The forest coverage increased obviously during 1980–2006. Its rapid growth from 38% to 54.7% between 1987 and 1994 was due to of the implementation of a large-scale reforestation program in Guangdong province. The average air temperatures also showed a significant increasing trend, especially

Table 4
Average contributions of climate change and reforestation on ET (1982–2006).

Components	Annual contributions (mm/year)	Contributions in humid seasons (mm/year)	Contributions in dry seasons (mm/year)
Reforestation	31.03	3.78	27.25
Climate change	−34.02	−5.84	−28.18
Total	−2.99	−2.06	−0.93

in dry seasons during the period 1980–2006. However, the increases of forest coverage and air temperature are most likely to play positive roles in increasing the regional ET, which is inconsistent with the current ET declining trends. So, only the precipitation variation trends are probably to cause the declining of Guangdong's ET. Correlation analysis results between ET and precipitation for period 1956–1979 and 1980–2006 were presented in Fig. 7 and Table 3. Result show that changes of precipitation correlated significantly with the ET variations in both two periods, with correlation coefficients equaling to 0.63 ($p < 0.001$) and 0.10 ($p < 0.001$) in humid seasons, and 0.91 ($p < 0.001$) and 0.91 ($p < 0.001$) in dry seasons. Precipitation is demonstrated to be mainly responsible for Guangdong's ET reductions.

The double mass curves of Guangdong's 50-year cumulative ET against the corresponding cumulative precipitation in both humid seasons and dry seasons were shown in Fig. 8. The contributions of climate change and reforestation on ET changes were listed in Table 4. Results indicate that there is no significant breakpoint on the humid-season double mass curve. But for the dry-season ET there is a significant breakpoint between 1980 and 1981 on the dry-season double mass curve. Climate change and reforestation contribute about −5.84 and 3.78 mm/year to the changes of humid-season ET, while −28.18 and 27.25 mm/year to the changes of dry-season ET, respectively. On the whole, the negative impacts of climate change on ET are −34.02 mm/year, by comparison with the 31.03 mm/year

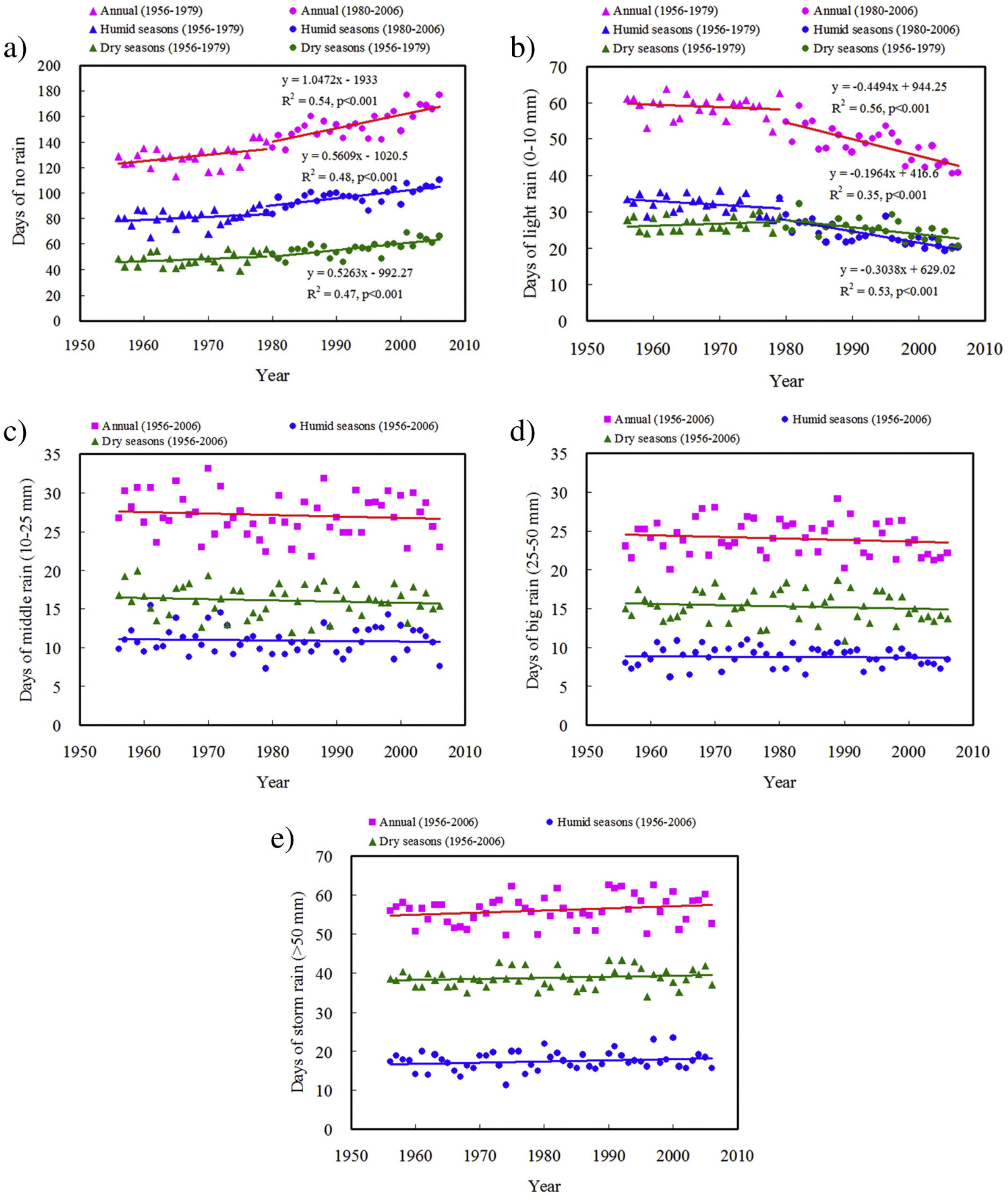

Fig. 9. Statistics of days with no-rain (a), light rain (b), middle rain (c), big rain (d) and storm rain (e) from 1956 to 2006.

positive impacts of reforestation. Results also show that both climate change and reforestation have more significant impacts on dry-season ET than that of humid seasons.

4. Discussions

4.1. The year of 1980 might be a change point of the hydrological processes

The double mass curves of Guangdong's ET against precipitation show that there is a significant breakpoint between 1980 and 1981 (Fig. 8). During the period 1956–1979, the humid- and dry-season precipitation and ET both remained much stable, while most of them varied much more significantly during the period 1980–2006 (Figs. 5 and 6a). The patterns of precipitation frequencies and amounts also varied little during the former period, but changed obviously during the later period, such as the days with no-rain and light rain, and total amounts of light rainfalls and storm rainfalls (Figs. 9 and 10). Above analysis indicates that the year of 1980 might be a change point of Guangdong's hydrological processes. The time-series variations of two main impact factors (air temperature and forest coverage data), which also changed suddenly around 1980, also partly support the breakpoint (Fig. 6b and c).

4.2. Roles of climate change and reforestation in influencing ET

Seen from Table 4, the contributions of climate change and reforestation in dry seasons are nearly 7.20 and 4.83 times respectively than those in humid seasons. It indicates that in dry seasons, Guangdong's regional ET is quite more sensitive to climate change and land cover changes, while much less sensitive in humid seasons. Comparing the contributions between climate change and reforestation, the negative impacts of climate change on ET (−34.02 mm/year) completely offset the positive impacts of reforestation (31.03 mm/year). In summary, climate change is the key factor controlling Guangdong's ET variation trends. Reforestation has relative less impact, especially in the humid seasons.

It is worth mentioning here that the influences of reforestation on ET changes differed greatly between humid (average P/PET = 1.95) and dry season (average P/PET = 0.77). Results suggest that in different climatic (P/PET) conditions or even different regions, the impact of forest management on hydrological processes would differ greatly. These could explain why former study results showed that forest removal or harvesting had positive (Bradshaw et al., 2007; Bruijnzeel, 2004; Jackson et al., 2005; Oudin et al., 2008), limited or even no effects on regional water resources (Antonio et al., 2008; Bruijnzeel, 2004; Buttle and Metcalfe, 2000; Dyhr-Nielsen, 1986; Jackson et al., 2005; Liu and Zhong, 1978; Ma, 1987; Wilk et al., 2001; Zhou et al., 2010). Our studies confirm the point of view that for the P/PET > 1, land cover changes would have little impacts on regional hydrological processes; while for the P/PET < 1, land cover changes would lead to greatly responses of regional water resources (Zhou et al., 2015). This conclusion might be useful for guiding government in future forest management. For example, afforestation would be actively encouraged in humid regions, but should be treated cautiously in non-humid regions or even be limited in arid regions.

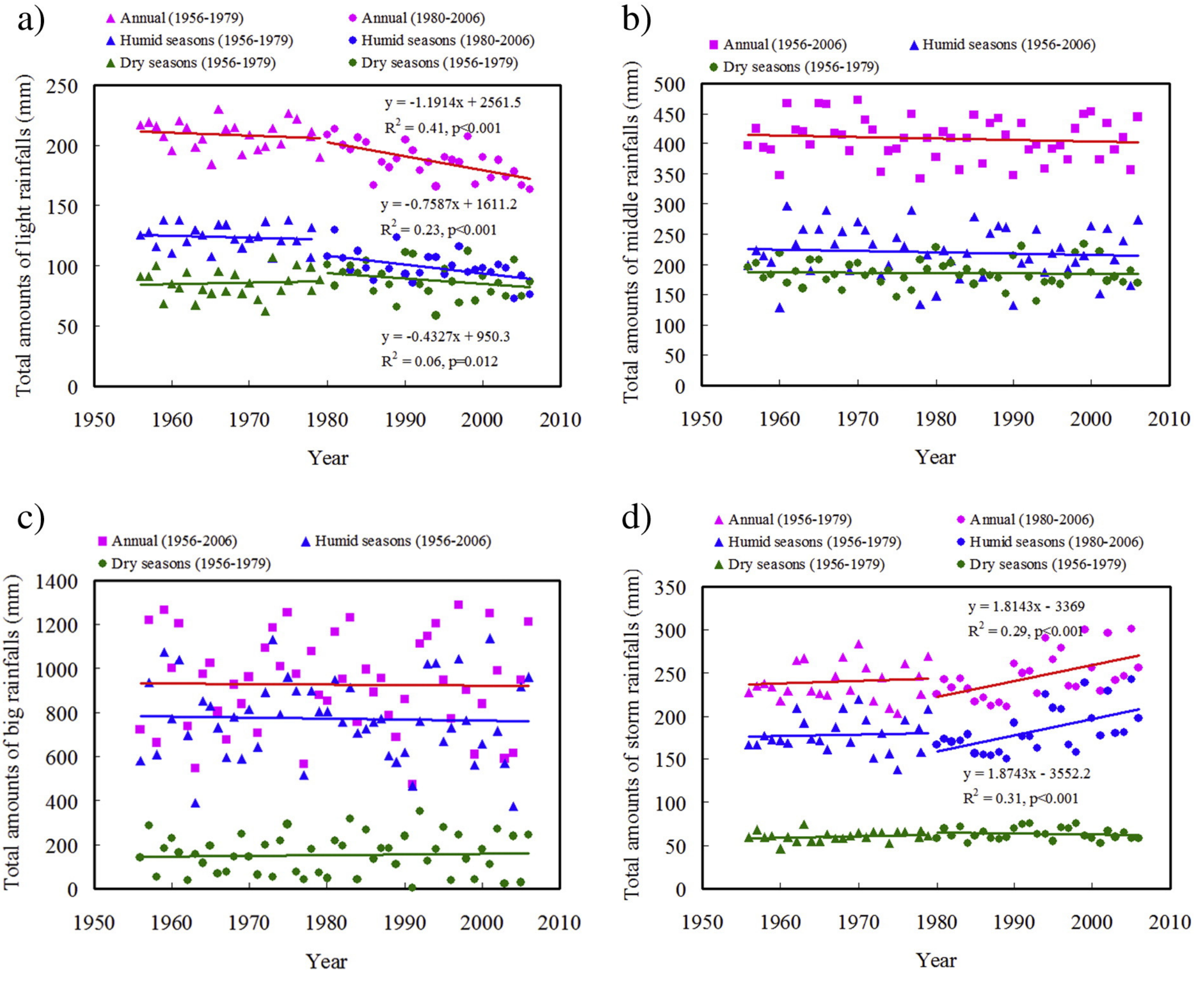

Fig. 10. Total amounts of light rainfalls (a), middle rainfalls (b), big rainfalls (c) and storm rainfalls (d) from 1956 to 2006.

4.3. Mechanisms for precipitation changes in reducing ET

The amounts and days of no-rain, light rain (0–10 mm), middle rain (10–25 mm), big rain (25–50 mm) and storm rain (>50 mm) of Guangdong province from 1956 to 2006 are shown in Figs. 9 and 10.

For humid seasons (1980–2006 period), more amount of precipitations fall in form of big rains and storms, which became river runoff quickly during the raining process and could not be stored up within the soil system and forest system for evapotranspiration, mainly due to their limited water holding capacity (Zhou et al, 2011). However, the deficit water storage in soil system and forest system couldn't be made up timely because of the decreasing days of light rains and increasing days of no-rain. Therefore, both precipitation pattern changes (increasing days of no-rain and decreasing days of light rain) and precipitation amount changes (decreasing amounts of light rain and increasing amounts of storm rainfalls) are responsible to the reduction of Guangdong's humid-season ET during the period 1980–2006.

For dry seasons (1980–2006 period), days of no-rain increase significantly, while days of light rain also decrease significantly. However, the amounts of precipitations in light, middle, big and storm rainfalls keep much stable. Therefore, precipitation pattern change (increasing days of no-rain and decreasing days of light rain), rather than the precipitation amount change, is the major contribution factor causing Guangdong's dry-season ET decreasing.

Overall, precipitation patterns as well as the total precipitation amounts are the major contribution factors causing Guangdong's ET decreasing, which were consistent with the opinion of Piao et al. (2009) and Zhou et al. (2011).

5. Conclusions

This paper detected that the time-series annual, humid-season and dry-season ET in general declined significantly ($p < 0.001$) during the 50 years. The year 1980 was an important turning point of Guangdong's hydrological processes. Precipitation pattern and amount changes were mainly responsible to the reduction of Guangdong's ET during the period 1980–2006. We also concluded that land cover changes would have little impacts on regional hydrological processes for the $P/PET > 1$, and would lead to greatly responses of regional water resources for the $P/PET < 1$. It is directly useful for guiding government in forest management.

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