The variations in potential evapotranspiration and the effects of environmental changes in a humid subtropical region

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Key Points:

- Potential evapotranspiration and its relationships with environmental factors are examined in a humid subtropical region across time scales.
- Variations in ETp are related to both meteorological and surface conditions including vegetation and soil water content.
- Summer saw the greatest changes in ETp per unit change in environmental variables, implying a greater water demand under a warming climate.

Abstract

Potential evapotranspiration (ETp) measures the ability of the atmosphere to remove water from the surface by evaporation and transpiration. Because the reference evapotranspiration is often used to infer this ability, ETp is usually considered only influenced by meteorological conditions. Due to the close linkages within the soil-vegetation-atmosphere system, ETp is likely influenced also by surface conditions like soil water content and vegetation cover. Therefore, this study is aimed at investigating the relationships between ETp and the associated environmental variables at different time scales. The results show that ETp has increased significantly by ~2.4 mm yr^{-1} during 1982-2015, alongside significant increase in vegetation index (NDVI), wind speed (Ws), temperatures and significant decrease in relative humidity (RH). Linear trends varied across seasons but similarities were found between spring and winter and between summer and autumn. Summer saw the greatest changes in ETp per unit change in environmental variables, which implies a likelihood of greater water demand with a warmer summer. Solar radiation, RH and precipitation exerted overall stronger influence on ETp (R^2>0.50) than other factors, and NDVI and SWC was found positively and negatively affecting ETp at all time scales (p>0.05 only for ETp-NDVI at annual scale). Furthermore, partial correlation analysis showed significant effects of NDVI and SWC on ETp at the monthly scale and SWC also influenced ETp in summers (p<0.05). This study proves that ETp is related to surface conditions in addition to meteorology, and shows the major factors effectively explaining the changes in ETp across different time scales.

Plain Language Summary

Potential evapotranspiration (ETp) measures the ability of atmosphere to remove water from the surface, and is often used to infer water demand in agriculture. ETp is considered only influenced by the atmospheric conditions such as temperature, radiation and humidity, while less is considered about the impacts of surface conditions such as vegetation and soil moisture. This study examined the variations and relationships between ETp and environmental variables in a humid subtropical region during 1982-2015. It is found that ETp has increased along with the wind speed, temperature, radiation and vegetation greenness, opposite to precipitation and soil moisture, hence the region has become warmer and drier. Linear regression and partial correlation analysis show that radiation and humidity are the two most influential factors for ETp changes across different time scales, while vegetation and soil moisture are more important at the monthly scale than seasonal and annual scales. ETp has increased the most in spring and winter, coincident with decreased precipitation and increased temperatures, which indicates that these two seasons are more prone to water shortage with the drying and warming tendency in the region. Moreover, water demand in summer is more sensitive to environmental changes than other seasons.

1. Introduction

Potential evapotranspiration (ETp) is defined by many researchers as the water escaping rate from a well-watered vegetated surface (Xiang et al., 2020). The vegetation characteristics on the surface can vary in different definitions, for example, Rosenberg

(1974) defined the ETp as “the evaporation from an extended surface of [a] short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water”, in which the vegetation features are implicit; while Allen et al., (1998) defined a reference grass with a fixed height of 0.12 m, a surface resistance of 70 s m^{-1}, and an albedo of 0.23, and hence their ETp is also known as the reference ET. The actual ET is positively related to ETp (Yang et al., 2020), but differs from ETp under most circumstances which can be explained in reference to the conditions imposed by the definition of ETp and the reality of these conditions. By any definitions, ETp measures the ability of the atmosphere to remove water from the surface through evaporation and transpiration (Kirkham, 2014). The two types of evapotranspiration are often considered for practical purposes of water resource management like guiding crop irrigation (Allen et al., 1998; Wen et al., 2016). ETp is an indispensable input variable for many land surface models and hydrologic models to calculate actual ET and other water budget components (Ala-aho et al., 2017; Chen & Dudhia, 2001), and plays a significant role in assessing regional dry and wet conditions and variations in meteorological conditions (Beguería et al., 2014; Vicente-Serrano et al., 2010; Yang et al., 2019; Zhang & Wang, 2021; Zhou et al., 2021). Therefore, quantification of ETp determines the performance of such models regarding the water flows, mixing and balances to better understand the climate impact on hydrology.

So far, various methods for ETp quantification have been developed involving different factors, such as the Thornthwaite model (Thornthwaite, 1948), the Priestley-Taylor equation (Priestley & Taylor, 1972), the Penman-Monteith equation (Monteith, 1965). They can be categorized into three types respectively, i.e. temperature-based, radiation-based, and the combination method, which have been compared extensively across a wide spectrum of climates and geolocations, and the combination method represented by the Penman-Monteith equation is considered superior to others in general (Fisher et al., 2011; Lu et al., 2005; Mallick et al., 2013; Oudin et al., 2005). Based on these methods a rich pool of ETp products have been produced, such as the GLEAM, MODIS, GLDAS, PML, etc. (Miralles et al., 2011; Mu et al., 2007; Rodell et al., 2004; Zhang et al., 2019). Previous studies have assessed the spatial patterns and seasonal variations of ETp and revealed the agreements and differences among many of these datasets (Jiménez et al., 2011; Mueller et al., 2011; Weiß & Menzel, 2008).

Composed of evaporation and transpiration processes, ETp is a function of meteorology and the surrounding environment (Zhan et al., 2019), therefore, ETp can vary simultaneously with changes in surface conditions, which has been proved by previous studies. For instance, Yang et al., (2011) claimed that relative humidity was the most influential factor followed by solar radiation and wind speed in the Yellow River Basin, whereas Wang et al., (2014) reported that temperature was the main reason for ETp change in a northern China irrigation district, followed by wind speed and relative humidity; Adnan et al., (2017) examined ET in arid and semi-arid zones in Pakistan and found it positively related with temperature, solar radiation, and wind speed while negatively related with air pressure; Duethmann & Blöschl (2018) found in over 150 Austrian catchments that the reference ET increased with increased net radiation and temperature; Zhang et al., (2020) found temperature and sunshine hours were the two most influential factors in Shangdong province, China; de Oliveira et al., (2021) found solar radiation was the most important factor controlling reference ET in the southern Amazon basin. These studies demonstrate that the weight of meteorological variables on ETp quantification varies with regions and scales. Although different (Xiang et al., 2020), the reference ET is often used as the potential ET in these studies due to its simplicity where vegetation parameters are fixed, so the impact of vegetation cover is rarely explored; and ETp is not limited by water supply by its definition so soil water condition is also neglected in the relationship analysis. This leaves meteorology the only factor governing ETp changes. However, because of the close connections in the soil-plant-atmosphere continuum regarding water flow and energy transfer, the divergent effects of surface conditions on near-surface meteorology and soil water content (Bonan, 1997; Jiao et al., 2021; Kaufmann et al., 2003), and the fact that ETp integrates the vegetation impacts through the 'surface resistance' that is influenced by many environmental factors (Buckley et al., 2003; Jarvis, 1976; Leuning, 1995; Wang et al., 2016), it is reasonable to hypothesize that ETp can be influenced by the changes in vegetation growth and soil water content besides meteorology, which however draws little attention so far and needs further justification.

Moreover, most of the previous studies are focused in the dry areas, less is known about the variations of ETp and its connections with meteorology, vegetation and soil water content in the humid areas. In our previous study in Guangdong, a southern province of China, we found that ETp has decreased by ~1 mm yr^{-1} during the water years of 2002-2014 (Zhou et al., 2021), comparable to other studies in some dry areas in spite of different study periods (Wang et al., 2014; Yang et al., 2011; Zhang et al., 2020). Given the role of ETp in the hydrologic cycles, it is important to assess the variations of ETp and comprehensively its influencing factors. Therefore, the overall aim of this study is to investigate the roles of meteorology, soil water content and vegetation in the ETp variation across different time scales. The specific objectives are (1) to examine the changes in potential ET alongside the influencing factors over the past 3 decades or so; and (2) to quantify the multiscale impacts of major meteorological variables, soil water content and vegetation on ETp.

2. Data and methods

2.1. Study area

Guangdong province in south China (Figure 1) has a subtropical monsoonal climate. The mean annual temperature is 22 °C, mean sunshine duration is around 1745 hours, and mean annual precipitation is 1780 mm ranging from 1300 to 2600 mm. Previous analysis showed that precipitation was overall on the rise in the province especially in the Pearl River Delta (Fu et al., 2016; Yan et al., 2020), while evapotranspiration decreased during 1980 to 2006 (Chen et al., 2015). Alongside the global warming tendency, the province confronts with water shortages induced by population growth, extreme weather and water contamination (Chen et al., 2014; Zhang et al., 2011). Quantification of water loss through evapotranspiration is important for water availability because ET accounts for over half the annual total precipitation on average in the region (Gao, 2010).

Vegetation cover in Guangdong province was low during 1980s, until the province launched a 10-year project to plant trees primarily over the mountains starting from around

1985. At present, 59.4% of the province is covered by forests, followed by croplands (23.8%) and urban areas (12.4%); the rest are covered by grassland, shrubland and other land use types, based on the 30-meter resolution land cover data (Gong et al., 2019). Elevated areas are mostly located in the north whereas lowlands are in the south where rivers converge and flow into the South China Sea (Figure 1).

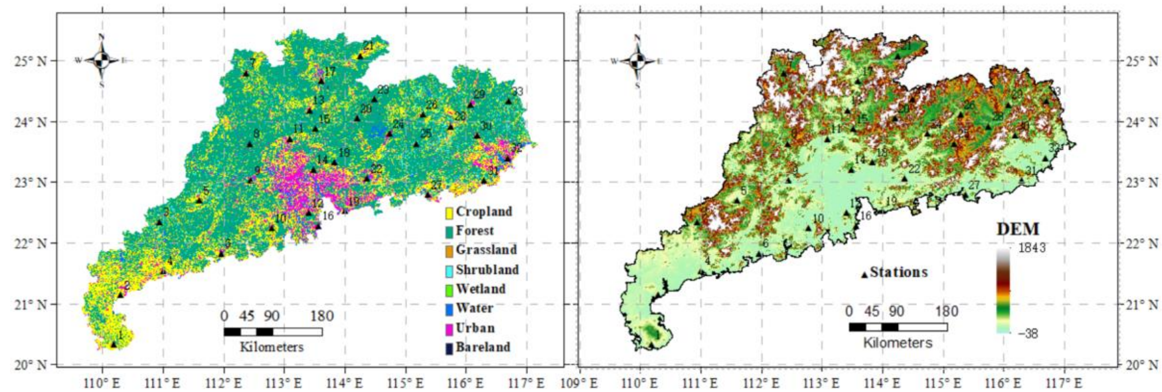

Figure 1 Land use land cover types of Guangdong province at a 30-meter resolution (left); and digital elevation map at a 1000-meter resolution (right). Locations of the meteorological stations are marked with black triangles with ID numbers.

2.2. Data sources

We obtained meteorological measurements at 33 stations from Chinese Meteorological Administration (http://data.cma.cn/data), covering different land use types and altitudes (Figure 1). These meteorological variables include the maximum, minimum and mean air temperature (Tmax, Tmin and Tavg, respectively), relative humidity (RH), wind speed (Ws) and directions, solar radiation (Rs), air pressure, and precipitation (P) at a monthly scale during 01/1982–12/2015. To assist the analysis of interaction between ETp and soil water condition, we obtained the GLEAM monthly 0.25° root-zone soil water content (SWC) data (Miralles et al., 2011) over the same period. Lastly, we used the biweekly 1/12° GIMMS NDVI3g vegetation index data (Pinzon & Tucker, 2014) to investigate the relationship between ETp and vegetation changes. Given that the interpolation with 33 stations across the province would lead to possible large uncertainty in those ungauged areas, we only analysed the temporal patterns and relationships using the spatially averaged data with their original spatial resolutions.

2.3. Calculation of ETp and analysis

Reference evapotranspiration based on the Penman-Monteith method (Allen et al., 1998) was calculated following equation (1), and the results were taken as the potential ET as in other studies.

$$ET_p = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

R_n is net radiation [MJ m^{-2} day^{-1}], G is soil heat flux [MJ m^{-2} day^{-1}]; Δ is slope of saturation vapor pressure curve [kPa°C^{-1}]; γ is psychrometric constant [kPa°C^{-1}]; T is air temperature [°C]; e_s and e_a is saturated and actual vapor pressure [kPa], and their difference is the vapor pressure deficit (VPD); u_2 is the wind speed at 2 m height about ground [m s^{-1}], calculated from wind speed observed at 10 m above ground (W_s) at the meteorological stations (equation 2, where z is the elevation above sea level of the stations).

$$u_2 = \frac{4.87W_s}{\log\left(67.8z - 5.42\right)} \quad (2)$$

The changing trends of ETp and the environmental variables were examined by the Mann-Kendall test. Relationships between ETp and the influencing factors were also investigated for different seasons under dry and wet conditions by linear regression analysis. Linear trends were removed from the data series before calculating the correlation coefficients for monthly, seasonal and annual scales. For monthly scale analysis, seasonality was also removed before detrending by subtracting the climatological means from monthly data. In addition, partial correlation analysis was applied to quantify the effect of environmental variables on ETp at the annual and monthly scales, which is widely used for studying the linear relationship between two variables after excluding the effect of other independent factors (Fu et al., 2015).

3. Results

3.1. Variations of ETp and the environmental variables

In general, the meteorological variables showed various annual dynamics, and the spatial variabilities were obvious indicated by the standard deviations (Figure 2). Precipitation has declined by ~3.7 mm yr^{-1} on average, but decreased in the first decade or so before it fluctuated irregularly. Root-zone soil water content showed similar pattern with precipitation in the first decade, while it decreased sharply around 2004 and then recovered rapidly. Abrupt change around 2004 was also observed for ETp and Rs which shared the most similar dynamic patterns. Among all variables, wind speed, mean/maximum/minimum annual temperatures, ETp and NDVI saw increases across the years at a rate of 0.1 m s^{-1}, 0.2, 0.3, 0.3 °C, 23.5 mm, and 0.012 per decade, respectively ($p<0.05$). Increasing trend also existed for solar radiation but not statistically significant. Overall decreasing trend was observed for humidity ($p<0.05$) and SWC ($p>0.05$) in addition to precipitation. Therefore, the study area has been getting dryer in general since 1980s, although it has been getting wetter since 2004 following a decreasing trend before that. In particular, the increase rate over the last 11 years was 3 and 11 times the decrease rate over the first 23 years for RH and SWC, respectively (Table 1). Wind speed and NDVI increased in both subperiods and the rate in the second subperiod was ~5 times that in the first. In addition, the increase rate of Tavg, Tmin and ETp in the recent decade was only 5%, 32% and 44% of that before 2004, whereas Tmax increased and then decreased over the two consecutive periods.

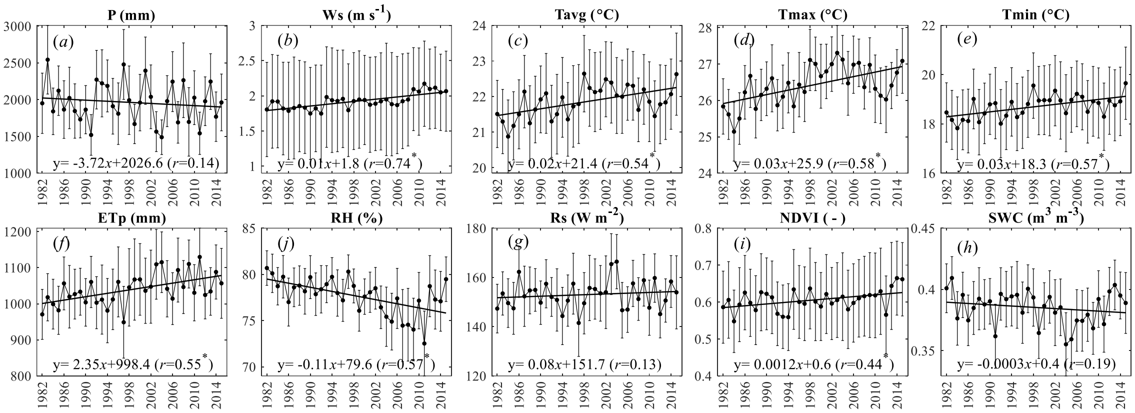

Figure 2 Annual variations of precipitation (P), wind speed (Ws), mean, maximum, minimum temperature (Tavg, Tmax, Tmin), relative humidity (RH), solar radiation (Rs), root-zone soil water content (SWC), normalized difference vegetation index (NDVI), and potential evapotranspiration (ETp). Solid straight lines infer linear trends of the relevant variables. Asterisks mark the significant trends.

Table 1 Linear trends of the investigated variables during three different periods at the annual scale. In bold are those with trends statistically significant.

Variables	1982-2015		1982-2004		2005-2015		Ratio of Trends*
	Trend	*p*	Trend	*p*	Trend	*p*	
P	-3.7195	0.443	-8.0129	0.389	-9.5983	0.706	1.20
Ws	**0.0080**	0.000	**0.0047**	0.031	**0.0237**	0.006	5.04
Tavg	**0.0239**	0.001	**0.0496**	0.000	0.0023	0.948	0.05
Tmax	**0.0309**	0.000	**0.0689**	0.000	-0.0107	0.787	-0.16
Tmin	**0.0252**	0.001	**0.0404**	0.002	0.0128	0.728	0.32
RH	**-0.1114**	0.000	**-0.1173**	0.003	0.3363	0.106	-2.87
Rs	0.0765	0.457	0.3071	0.105	0.4526	0.417	1.47
NDVI	**0.0012**	0.009	**0.0012**	0.009	**0.0062**	0.024	5.17
SWC	-0.0003	0.274	-0.0003	0.274	**0.0033**	0.006	-11.00
ETp	**2.3512**	0.001	**3.5001**	0.004	1.5404	0.696	0.44

*The ratio is calculated as trend over 2005-2015 divided by that over 1982-2004.

We also investigated the monthly climatological variations between the two subperiods (Figure 3) to compare them in different months of the year. It is observed that all variables showed clear seasonality. The peak values for P, RH and SWC appeared in June, whereas it was July for temperatures, ETp and Rs. NDVI peaked in mid-autumn (October) and lowest value occurred in early spring (March). Over the two periods, wind speed, temperature, vegetation index and potential ET were overall higher while precipitation and relative humidity were mostly lower in the recent decade that previously. Hence, the province has been getting warmer and drier, even though the Wilcoxon rank sum test indicated only wind speed had statistically significant difference between the two subperiods. The comparison also shows that dynamic changes of these variables varied across months. For instance, precipitation increased during May, June, November and

December, and consequently, solar radiation in these months decreased; December and January got cooler after 2005 than before 2005; vegetation greenness saw a decrease in June and October; and root-zone soil water decreased primarily in spring and increased slightly in summer and autumn. Decrease in ETp in June corresponded to increase in P, decrease in Rs and NDVI.

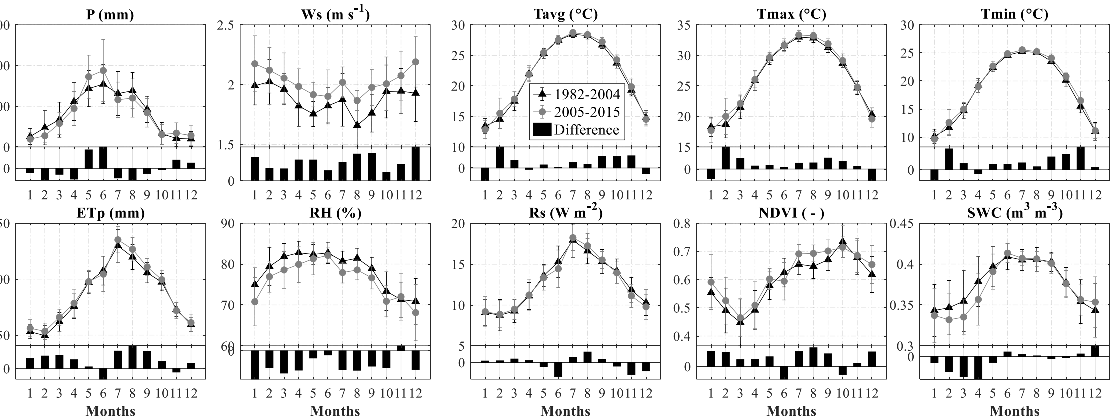

Figure 3 Monthly climatological means of the investigated variables during 1982-2004 and 2005-2015. The bars below are the residuals with values in 2005-2015 subtracted by these in 1982-2004.

Furthermore, we examined their interannual variations in different seasons in Figure 4 and Table 2 which show various changing patterns. Ws has increased significantly at nearly the same rate across all seasons, while RH has decreased significantly (more in spring and winter than summer and autumn). For temperatures, Tavg, Tmax and Tmin have all increased across all seasons with different magnitudes, but the significant increase appeared in spring and autumn for Tavg, spring, summer and autumn for Tmax, and summer and autumn for Tmin. Root-zone SWC saw an increase only in summer and largest decrease occurred in spring (p<0.05), consistent with precipitation and RH. Rs has increased in spring and winter and decreased in summer and autumn (p>0.05 for all). NDVI has increased across all seasons and significant and largest increase appeared in spring and winter. Seasonal ETp trends shared the same characteristics with NDVI in terms of significant increasing trends in spring and winter. Apart from the trends, the highs and lows of these variables appeared in different seasons, for example, precipitation, temperatures, radiation, soil water content and ETp were highest in summer and lowest in winter, while humidity was higher in spring and summer than autumn and winter, and NDVI was highest in autumn and lowest in spring.

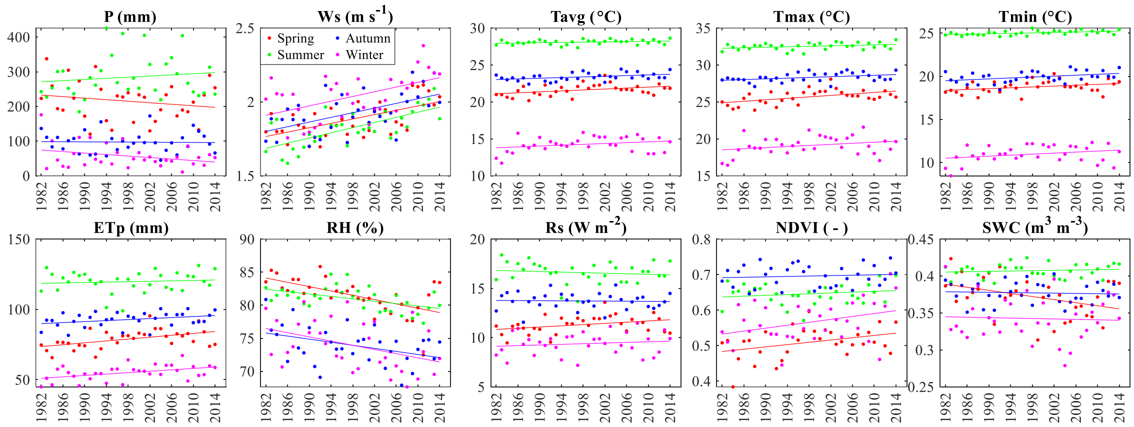

Figure 4 Seasonal trends of the investigated variables over the province during 1982-2015. Lines are linear regressions for different seasons.

Table 2 Linear trends and *p* values for the variables in Figure 4. In bold are trends with $p<0.05$.

Variables	Spring		Summer		Autumn		Winter	
	Trend	*p*	Trend	*p*	Trend	*p*	Trend	*p*
P	-1.1057	0.281	0.8273	0.465	-0.0854	0.880	-1.0750	0.088
Ws	**0.0074**	0.000	**0.0087**	0.000	**0.0079**	0.001	**0.0080**	0.002
Tavg	**0.0320**	0.018	0.0094	0.119	**0.0224**	0.015	0.0288	0.123
Tmax	**0.0496**	0.002	**0.0165**	0.048	**0.0242**	0.024	0.0368	0.114
Tmin	0.0247	0.051	**0.0131**	0.004	**0.0266**	0.021	0.0295	0.110
RH	**-0.1635**	0.000	**-0.0907**	0.004	**-0.1164**	0.022	**-0.1584**	0.017
Rs	0.0308	0.054	-0.0138	0.491	-0.0032	0.839	0.0162	0.436
NDVI	**0.0016**	0.036	0.0006	0.315	0.0003	0.610	**0.0021**	0.046
SWC	**-0.0010**	0.033	0.0001	0.505	-0.0001	0.724	-0.0001	0.790
ETp	**0.3355**	0.004	0.0749	0.589	0.1790	0.055	**0.2496**	0.008

3.2. Multiscale impacts of environmental factors on ETp

The impacts of the factors on ETp were examined by linear regression and partial correlation analysis at different time scales. The annual ETp were plotted against these influencing factors in Figure 5, which shows that the linear relationships were significant for P, Tmax, RH, Rs and SWC ($p<0.05$). The strongest impact factor determined by the correlation coefficient was Rs, followed by P, RH, SWC and Tmax ($r=0.93$, -0.74, -0.71, -0.59, and 0.40, respectively). Correlation coefficient for other factors were mostly less than 0.20. ETp increased with wind speed, mean and maximum temperatures, solar radiation and vegetation greenness, while decreased with precipitation, minimum temperature, relative humidity and soil water content. Increase in maximum temperature can promote ETp more than average and minimum temperatures, which indicates that the atmospheric demand in the region would grow strongly with enhanced global warming.

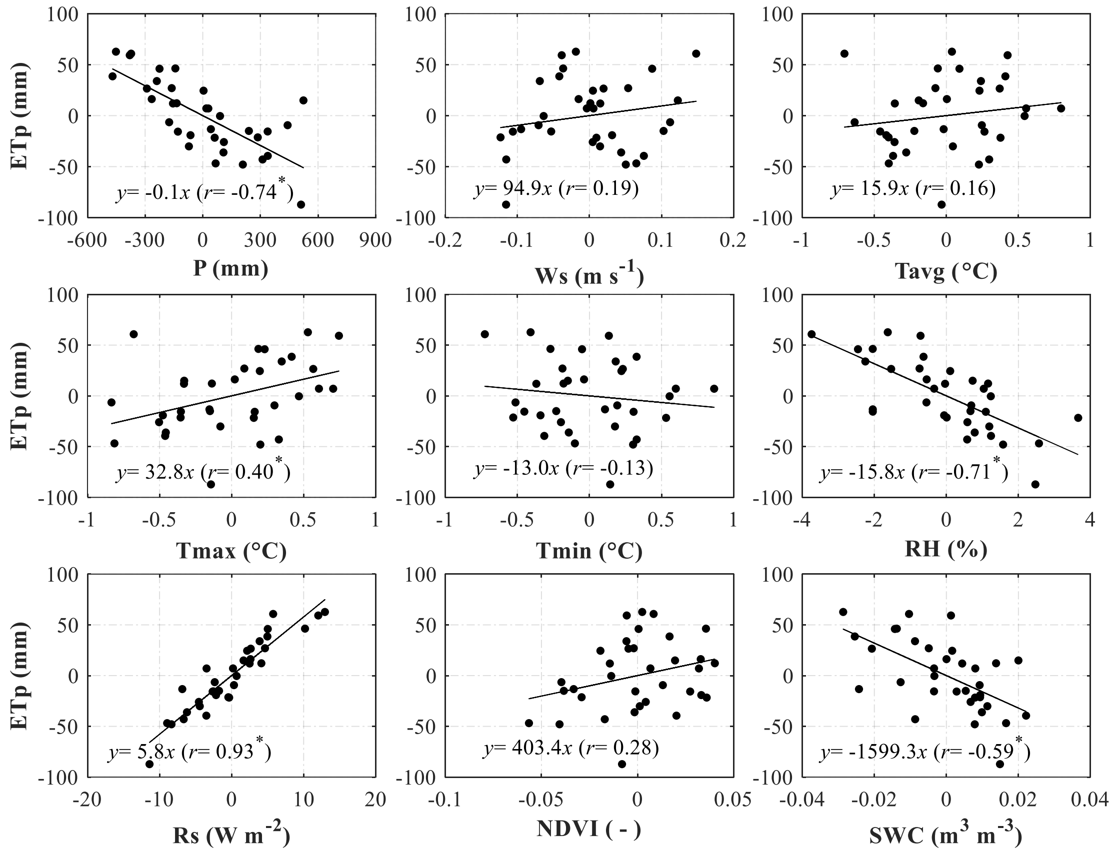

Figure 5 Scatterplots of annual ETp against different variables over the entire province. Data were detrended. Asterisk infers a statistically significant linear relationship.

The relationships showed different characteristics in different seasons (Figure 6). For example, ETp would increase the most in summer and least in winter with 1 °C increase in temperatures. The regression slopes were largest in summer and lowest in winter for almost all variables, that is, ETp was most sensitive to environmental changes in summer and least in winter. The difference between slopes in summer and winter was substantial for temperatures (e.g., Tavg: 19.76 vs. 1.56), RH (16.97 vs. -0.04), NDVI (173.00 vs. 39.26) and SWC (-592.02 vs. -72.95). Opposite effects (positive or negative) of Ws and Tmin across different seasons were observed. Similar to the relationships at the annual scale, seasonal ETp was also most strongly influenced by Rs, P, RH (R^2>0.50). For some influencing factors, even if the relationships were not statistically significant at the annual scale, they may be significant in different seasons, e.g., Tavg, Tmin and ETp in spring and summer. Annual NDVI was not significantly related to ETp but their relationships were significant in every season.

In Figure 6, the black lines are linear regressions of data pairs in all seasons, which in some way is representative of monthly relationships since the seasonal data were calculated as the mean of the three months in each season. The correlation coefficients ranged from 0.10 (for Tmin) to 0.94 (for Rs) and were statistically significant for all except Ws and Tmin (black numbers in Figure 6). The degree of influence reduced in the sequence of Rs, P, RH, Tmax, NDVI, SWC and Tavg with a correlation coefficient of 0.94, -0.76, -0.73, 0.61, 0.48,

-0.47, and 0.40, respectively. To sum up, potential ET increased with wind speed, temperatures, solar radiation and vegetation greenness, and decreased with precipitation, relative humidity and soil water content across different time scales; meanwhile, the relationships presented different characteristics among seasons.

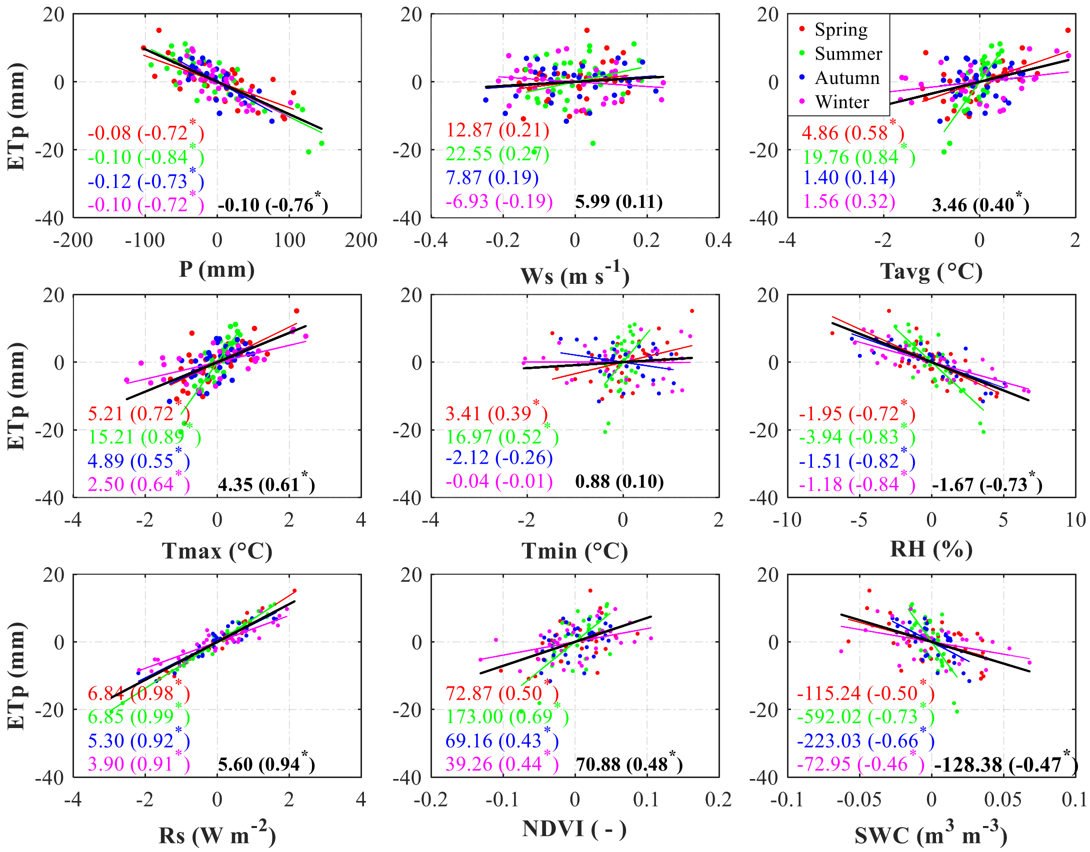

Figure 6 Scatterplots of ETp against different variables in different seasons. All data were detrended. Black lines are regression results for data in all seasons which is equivalent to monthly data regression. Numbers outside and inside the brackets are regression slopes and correlation coefficients, respectively. Asterisks infer statistically significant linear regressions.

To determine the degree of influence of each environmental variable on ETp and the interactions between these variables, we carried out partial correlation analysis. The partial correlation coefficients were given in Table 3, which showed that the environmental variables played different roles in determining ETp at different time scales. For annual data, the three most influential factors were solar radiation, relative humidity and wind speed (r=0.88, -0.87, 0.73, respectively, with p<0.05); maximum temperature also posed a significant negative effect (r=-0.51). The influence of other environmental factors was not statistically significant. For monthly data, influences of Rs, RH and Ws were also stronger than others (r=0.94, -0.46 and 0.33 with p<0.05), and the influences of Tmax, Tmin, NDVI and SWC were also statistically significant although correlation coefficients were relatively low. For seasonal data, Rs, RH and Ws were still the strongest factors affecting ETp, and the impacts were overall stronger in summer and autumn than spring and winter. In summer, SWC also had a significant positive impact on ETp (r=0.46), while in autumn

P and Tmax had significant negative impacts (r=-0.49 & -0.41) in addition to Rs, RH and Ws. Therefore, in a relatively short time such as a month, ETp tends to be influenced by more environmental variables than in a relatively long time such as a season or a year; and the relationships presented both common and unique characteristics across seasons.

Table 3 Partial correlation coefficients (r) between ETp and the relevant environmental variables. In bold are correlation coefficients with p<0.05.

	Annual	Monthly	Spring	Summer	Autumn	Winter
P	-0.24	0.01	-0.24	-0.30	**-0.49**	0.16
Ws	**0.73**	**0.33**	**0.62**	**0.86**	**0.87**	**0.63**
Tavg	0.34	-0.10	-0.08	0.39	0.37	-0.22
Tmax	**-0.51**	**-0.14**	-0.12	-0.08	**-0.41**	0.23
Tmin	-0.03	**0.30**	0.31	0.27	-0.14	0.35
RH	**-0.87**	**-0.46**	**-0.77**	**-0.95**	**-0.87**	**-0.85**
Rs	**0.88**	**0.94**	**0.94**	**0.99**	**0.93**	**0.79**
NDVI	-0.19	**-0.20**	0.10	-0.02	-0.26	-0.31
SWC	0.19	**-0.11**	-0.18	**0.46**	-0.19	-0.14

4. Discussion

ETp is an important component in the simple water balance equation to indicate water deficit or surplus (Wu et al., 2019) which integrates the effects of climate and surface conditions, and is often deducted by a series of environmental stress functions to estimate actual ET (Guerschman et al., 2009; Mu et al., 2011; Wang et al., 2020). Assessing the changes in ETp and its relationships with major associated influencing factors is necessary towards improving ET estimation and understanding the future climate change impacts on water resources. In this humid subtropical region, we found ETp has increased by ~2.35 mm yr^{-1} during 1982-2015 (p<0.05), and the increase rate in the first 2 decades was twice as much as the recent decade. Alongside the ETp change was an overall decrease in P, while RH and root-zone SWC shared similar pattern that they decreased over the entire period and the first 2 decades but increased over the last decade, and the increase rate was greater than the decrease rate. In fact, the change rate over 2005-2015 was greater than that over 1982-2004 for nearly all variables. This indicates that in the recent decade or so, the climate activities are enhanced (Yang et al., 2018) and the region gets drier and warmer. Down to seasons, ETp was highest in summer and lowest in winter, different from that in a province in north China (Zhang et al., 2020). The changes in ETp and the environmental variables presented different seasonal features, e.g., rainfall and SWC increased only in summer, different from the result in Pearl River basin during 1961-2007 by Gemmer et al., (2011); meanwhile, Rs increased in spring and winter while decreased in summer and autumn; ETp and NDVI increased in all seasons and higher increase rate was in spring and winter. These detailed features are rarely reported before, but important to understand the soil-vegetation-atmosphere interactions across scales in the humid subtropical areas.

The impacts of environmental variables on ETp showed both similarity and difference across time scales. Namely, ETp was negatively correlated with P, Tmin, RH and SWC and positively with other variables at the annual scale, which is highly similar at the monthly scale. However, when it comes to seasonal data, the sensitivity of ETp to these variables was different, i.e. ETp is most sensitive to environmental changes in summer and least sensitive in winter. This implies that the water demand in the region will increase more in summer than other seasons with a certain increase in temperature (Wang et al., 2018; Zhang et al., 2018). In the meantime, ETp has increased the most in spring and winter, coincident with decreased precipitation and increased temperatures, which indicates that these two seasons are more prone to water shortages with the drying and warming tendency in the region.

When calculated following the Allen et al., (1998) method, ETp is considered as only affected by meteorological factors. While in studies carried out in southern Amazon basin in Brazil and northwest China's Qilian mountains (de Oliveira et al., 2021; Yang et al., 2020) the resultant ETp was found to have different values and trends over different land cover types, which implies that ETp is closely related to surface conditions whether or not these conditions are formulated in the reference evapotranspiration equation. If quantified by the Penman-Monteith equation with site-specific surface resistance (Chen & Dudhia, 2001; Mallick et al., 2015; Xiang et al., 2020), rather than a fixed value, ETp would be more strongly related to surface conditions including vegetation and soil moisture. Our study shows that annual ETp varies significantly with root-zone moisture, but insignificantly with vegetation greenness, while the monthly and seasonal relationships are statistically significant. Partial correlation analysis demonstrates the weights of each variable determining ETp which are clearly different across time scales and in four seasons. The most weighed factors are Rs and RH. Both NDVI and SWC played a negative role at the monthly scale, and SWC is the fourth important factor influencing summer ETp. At the other time scales or in other seasons, the role of NDVI and SWC is not statistically significant. Nevertheless, analysis of the impacts of surface conditions on ETp would improve our understanding of the connections in the soil-plant-atmosphere continuum, and hence help to better manage and mitigate the climate change impacts on water resources through optimization of the surface conditions at both temporal and spatial scales.

5. Conclusions

This study examined the variations in potential evapotranspiration (ETp) and its relationships with the associated environmental factors across time scales. Surrogated by the reference evapotranspiration, ETp is considered to be only affected by meteorology, however, we found in our humid subtropical region that vegetation and root-zone soil moisture also influenced ETp even though the partial correlation coefficients were relatively low (mostly within ± 0.30, and only statistically significant at the monthly scale for both factors and in summer for soil moisture). The most influential factors are solar radiation (positive effect), followed by precipitation and relative humidity (negative effects); the impacts of other factors varied across time scales and seasons. ETp has increased the most in spring and winter, coincident with decreased precipitation and increased temperatures, which indicates that these two seasons are more prone to water shortage issues with the drying and warming tendency in the region. Moreover, changes in ETp with per unit change in environmental variables were highest in summer, which implies likely greater water demand in summer than other seasons with a warming climate.

If quantified through the Penman-Monteith equation with site-specific surface resistance, ETp would be more strongly related to vegetation and soil moisture than using reference evapotranspiration.

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Data Availability Statement

The meteorological data from 33 stations together with extracted root-zone soil water content and NDVI data can be found at the Mendeley data repository (DOI: 10.17632/yypv8m89mb.1). Original GIMMS NDVI3g data can be found at https://ecocast.arc.nasa.gov/data/pub/gimms; Original GLEAM data can be found at www.gleam.eu.

References

Adnan, S., Ullah, K., Khan, A. H., & Gao, S. (2017). Meteorological impacts on evapotranspiration in different climatic zones of Pakistan. *Journal of Arid Land*, *9*(6), 938–952. https://doi.org/10.1007/s40333-017-0107-2

Ala-aho, P., Soulsby, C., Wang, H., & Tetzlaff, D. (2017). Integrated surface-subsurface model to investigate the role of groundwater in headwater catchment runoff generation: A minimalist approach to parameterisation. *Journal of Hydrology*, *547*, 664–677. https://doi.org/10.1016/j.jhydrol.2017.02.023

Allen, R. G., Luis, P. S., Dirk, R., & Smith, M. (1998). *Crop Evapotranspiration (guidelines for computing crop water requirements)*. *FAO Irrigation and drainage paper 56*. Rome, Italy. Retrieved from http://www.kimberly.uidaho.edu/water/fao56/fao56.pdf

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Bonan, G. B. (1997). Effects of land use on the climate of the United States. *Climatic Change*, *37*(3), 449–486. https://doi.org/10.1023/A:1005305708775

Buckley, T. N., Mott, K. A., & Farquhar, G. D. (2003). A hydromechanical and biochemical model of stomatal conductance. *Plant, Cell and Environment*, *26*(10), 1767–1785. https://doi.org/10.1046/j.1365-3040.2003.01094.x

Chen, F., & Dudhia, J. (2001). Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity. *Monthly Weather Review*, 569–585.

Chen, X., Liu, X., Zhou, G., Han, L., Liu, W., & Liao, J. (2015). 50-year evapotranspiration declining and potential causations in subtropical Guangdong province, southern China. *Catena*, *128*, 185–194. https://doi.org/10.1016/j.catena.2015.02.001

Chen, Z., Zhu, Z., Yin, L., Wei, S., & Deng, L. (2014). The Changing Water Quality Characteristics from Urban Drinking Water Sources in Guangdong, China. *Water Resources Management*, *29*(4), 987–1002. https://doi.org/10.1007/s11269-014-0855-0

Duethmann, D., & Blöschl, G. (2018). Why has catchment evaporation increased in the past 40 years? A data-based study in Austria. *Hydrology and Earth System Sciences Discussions*, 1–24. https://doi.org/10.5194/hess-2018-129

Fisher, J. B., Whittaker, R. J., & Malhi, Y. (2011). ET come home: Potential evapotranspiration in geographical ecology. *Global Ecology and Biogeography*, *20*(1), 1–18. https://doi.org/10.1111/j.1466-8238.2010.00578.x

Fu, S., Li, D., Sun, J., Si, D., Ling, J., & Tian, F. (2016). A 31-year trend of the hourly precipitation over South China and the underlying mechanisms. *Atmospheric Science Letters*, *17*(3), 216–222. https://doi.org/10.1002/asl.645

Fu, Y. H., Piao, S., Vitasse, Y., Zhao, H., De Boeck, H. J., Liu, Q., et al. (2015). Increased heat requirement for leaf flushing in temperate woody species over 1980-2012: Effects of chilling, precipitation and insolation. *Global Change Biology*, *21*(7), 2687–2697. https://doi.org/10.1111/gcb.12863

Gao, X. (2010). *Actual Evapotranspiration in the Pearl River Basin: Estimation, Spatio-Temporal Variations and Climatic Sensitivities*. The Chinese University of Hong Kong. https://doi.org/10.1017/S0033291717001520

Gemmer, M., Fischer, T., Jiang, T., Su, B., & Liu, L. L. (2011). Trends in precipitation extremes in the Zhujiang River basin, South China. *Journal of Climate*, *24*(3), 750–761. https://doi.org/10.1175/2010JCLI3717.1

Gong, P., Liu, H., Zhang, M., Li, C., Wang, J., Huang, H., et al. (2019). Stable classification with limited sample: transferring a 30-m resolution sample set collected in 2015 to mapping 10-m resolution global land cover in 2017. *Science Bulletin*, *64*(6), 370–373. https://doi.org/10.1016/j.scib.2019.03.002

Guerschman, J. P., Van Dijk, A. I. J. M., Mattersdorf, G., Beringer, J., Hutley, L. B., Leuning, R., et al. (2009). Scaling of potential evapotranspiration with MODIS data reproduces flux observations and catchment water balance observations across Australia. *Journal of Hydrology*, *369*(1–2), 107–119. https://doi.org/10.1016/j.jhydrol.2009.02.013

Jarvis, P. G. (1976). The Interpretation of the Variations in Leaf Water Potential and Stomatal Conductance Found in Canopies in the Field. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *273*(927), 593–610. https://doi.org/10.1098/rstb.1976.0035

Jiao, W., Wang, L., Smith, W. K., Chang, Q., Wang, H., & D'Odorico, P. (2021). Observed increasing water constraint on vegetation growth over the last three decades. *Nature Communications*, *12*(1), 1–9. https://doi.org/10.1038/s41467-021-24016-9

Jiménez, C., Prigent, C., Mueller, B., Seneviratne, S. I., McCabe, M. F., Wood, E. F., et al. (2011). Global intercomparison of 12 land surface heat flux estimates. *Journal of Geophysical Research Atmospheres*, *116*(2), 1–27. https://doi.org/10.1029/2010JD014545

Kaufmann, R. K., Zhou, L., Myneni, R. B., Tucker, C. J., Slayback, D., Shabanov, N. V., & Pinzon, J. (2003). The effect of vegetation on surface temperature: A statistical analysis of NDVI and climate data. *Geophysical Research Letters*, *30*(22), 2147. https://doi.org/10.1029/2003GL018251

Kirkham, M. B. (2014). Potential Evapotranspiration. In *Principles of Soil and Plant Water Relations* (pp. 501–514). Elsevier. https://doi.org/10.1016/b978-0-12-420022-7.00028-8

Leuning, R. (1995). A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. *Plant, Cell & Environment*, *18*(4), 339–355. https://doi.org/10.1111/j.1365-3040.1995.tb00370.x

Lu, J., Sun, G., McNulty, S. G., & Amatya, D. M. (2005). A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *Journal of the American Water Resources Association*, *41*(3), 621–633. https://doi.org/10.1111/j.1752-1688.2005.tb03759.x

Mallick, K., Jarvis, A., Fisher, J. B., Tu, K. P., Boegh, E., & Niyogi, D. (2013). Latent heat flux and canopy conductance based on Penman-Monteith, Priestley-Taylor equation, and Bouchet's complementary hypothesis. *Journal of Hydrometeorology*, *14*(2), 419–442. https://doi.org/10.1175/JHM-D-12-0117.1

Mallick, K., Boegh, E., Trebs, I., Alfieri, J. G., Kustas, W. P., Prueger, J. H., et al. (2015). Reintroducing radiometric surface temperature into the Penman-Monteith formulation. *Water Resources Research*, 6214–6243. https://doi.org/10.1002/2014WR016106.Received

Miralles, D. G., De Jeu, R. A. M., Gash, J. H., Holmes, T. R. H., & Dolman, A. J. (2011). Magnitude and variability of land evaporation and its components at the global scale. *Hydrology and Earth System Sciences*, *15*(3), 967–981. https://doi.org/10.5194/hess-15-967-2011

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*.

Mu, Q., Heinsch, F. A., Zhao, M., & Running, S. W. (2007). Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment*, *111*, 519–536. https://doi.org/10.1016/j.rse.2006.07.007

Mu, Q., Zhao, M., & Running, S. W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment*, *115*(8), 1781–1800. https://doi.org/10.1016/j.rse.2011.02.019

Mueller, B., Seneviratne, S. I., Jimenez, C., Corti, T., Hirschi, M., Balsamo, G., et al. (2011). Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations. *Geophysical Research Letters*, *38*(6), 1–7. https://doi.org/10.1029/2010GL046230

de Oliveira, R. G., Valle Júnior, L. C. G., da Silva, J. B., Espíndola, D. A. L. F., Lopes, R. D., Nogueira, J. S., et al. (2021). Temporal trend changes in reference evapotranspiration contrasting different land uses in southern Amazon basin. *Agricultural Water Management*, *250*, 106815. https://doi.org/10.1016/j.agwat.2021.106815

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., & Loumagne, C. (2005). Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 - Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. *Journal of Hydrology*, *303*(1–4), 290–306. https://doi.org/10.1016/j.jhydrol.2004.08.026

Pinzon, J. E., & Tucker, C. J. (2014). A non-stationary 1981-2012 AVHRR NDVI3g time series. *Remote Sensing*, *6*(8), 6929–6960. https://doi.org/10.3390/rs6086929

Priestley, C. H. B., & Taylor, R. J. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. Retrieved June 22, 2021, from https://journals.ametsoc.org/view/journals/mwre/100/2/1520-0493_1972_100_0081_otaosh_2_3_co_2.xml

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C. J., et al. (2004). The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-85-3-381

Rosenberg, N. J. (1974). *Microclimate: The Biological Environment*. New York: John Wiley & Sons, Inc.

Thornthwaite, C. W. (1948). An Approach toward a Rational Classification of Climate. *Geographical Review*, *38*(1), 55. https://doi.org/10.2307/210739

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Wang, H., Guan, H., & Simmons, C. T. (2016). Modeling the environmental controls on tree water use at different temporal scales. *Agricultural and Forest Meteorology*, *225*, 24–35. https://doi.org/10.1016/j.agrformet.2016.04.016

Wang, H., Guan, H., Liu, N., Soulsby, C., Tetzlaff, D., & Zhang, X. (2020). Improving the Jarvis-type model with modified temperature and radiation functions for sap flow simulations. *Journal of Hydrology*, *587*, 124981. https://doi.org/10.1016/j.jhydrol.2020.124981

Wang, X. M., Liu, H. J., Zhang, L. W., & Zhang, R. H. (2014). Climate change trend and its effects on reference evapotranspiration at Linhe Station, Hetao Irrigation District. *Water Science and Engineering*, *7*(3), 250–266. https://doi.org/10.3882/j.issn.1674-2370.2014.03.002

Wang, Z., Zhong, R., Lai, C., Zeng, Z., Lian, Y., & Bai, X. (2018). Climate change enhances the severity and variability of drought in the Pearl River Basin in South China in the 21st century. *Agricultural and Forest Meteorology*, *249*(December 2017), 149–162. https://doi.org/10.1016/j.agrformet.2017.12.077

Weiß, M., & Menzel, L. (2008). A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. *Advances in Geosciences*, *18*, 15–23. https://doi.org/10.5194/adgeo-18-15-2008

Wen, X., Yang, B., Sun, X., & Lee, X. (2016). Evapotranspiration partitioning through in-situ oxygen isotope measurements in an oasis cropland. *Agricultural and Forest Meteorology*, *230–231*, 89–96. https://doi.org/10.1016/j.agrformet.2015.12.003

Wu, X., Guo, W., Liu, H., Li, X., Peng, C., Allen, C. D., et al. (2019). Exposures to temperature beyond threshold disproportionately reduce vegetation growth in the northern hemisphere. *National Science Review*, *6*(4), 786–795. https://doi.org/10.1093/nsr/nwy158

Xiang, K., Li, Y., Horton, R., & Feng, H. (2020). Similarity and difference of potential evapotranspiration and reference crop evapotranspiration – a review. *Agricultural Water Management*, *232*(August 2019). https://doi.org/10.1016/j.agwat.2020.106043

Yan, M., Chan, J. C. L., & Zhao, K. (2020). Impacts of Urbanization on the Precipitation Characteristics in Guangdong Province, China. *Advances in Atmospheric Sciences*, *37*(7), 696–706. https://doi.org/10.1007/s00376-020-9218-3

Yang, L., Feng, Q., Adamowski, J. F., Alizadeh, M. R., Yin, Z., Wen, X., & Zhu, M. (2020). The role of climate change and vegetation greening on the variation of terrestrial evapotranspiration in northwest China's Qilian Mountains. *Science of the Total Environment*, *759*, 143532. https://doi.org/10.1016/j.scitotenv.2020.143532

Yang, L. E., Chan, F. K. S., & Scheffran, J. (2018). Climate change, water management and stakeholder analysis in the Dongjiang River basin in South China. *International Journal of Water Resources Development*, *34*(2), 166–191. https://doi.org/10.1080/07900627.2016.1264294

Yang, Y., Roderick, M. L., Zhang, S., McVicar, T. R., & Donohue, R. J. (2019, January 1). Hydrologic implications of vegetation response to elevated CO2 in climate projections. *Nature Climate Change*. Nature Publishing Group. https://doi.org/10.1038/s41558-018-0361-0

Yang, Z., Liu, Q., & Cui, B. (2011). Distribution spatiale et variation temporelle de l'évapotranspiration de référence pendant la période 1961-2006 dans le bassin du Fleuve Jaune, en Chine. *Hydrological Sciences Journal*, *56*(6), 1015–1026. https://doi.org/10.1080/02626667.2011.590810

Zhan, S., Song, C., Wang, J., Sheng, Y., & Quan, J. (2019). A Global Assessment of Terrestrial Evapotranspiration Increase Due to Surface Water Area Change. *Earth's Future*, *7*(3), 266–282. https://doi.org/10.1029/2018EF001066

Zhang, F., Liu, Z., Zhangzhong, L., Yu, J., Shi, K., & Yao, L. (2020). Spatiotemporal distribution characteristics of reference evapotranspiration in shandong province from 1980 to 2019. *Water (Switzerland)*, *12*(12), 1–16. https://doi.org/10.3390/w12123495

Zhang, H., & Wang, L. (2021). Analysis of the variation in potential evapotranspiration and surface wet conditions in the Hancang River Basin, China. *Scientific Reports*, *11*(8607). https://doi.org/10.1038/s41598-021-88162-2

Zhang, Q., Zhang, W., Chen, Y. D., & Jiang, T. (2011). Flood, drought and typhoon disasters during the last half-century in the Guangdong province, China. *Natural Hazards*. https://doi.org/10.1007/s11069-010-9611-9

Zhang, Q., Li, J., Gu, X., & Shi, P. (2018). Is the Pearl River basin, China, drying or wetting? Seasonal variations, causes and implications. *Global and Planetary Change*, *166*(May), 48–61. https://doi.org/10.1016/j.gloplacha.2018.04.005

Zhang, Y., Kong, D., Gan, R., Chiew, F. H. S., McVicar, T. R., Zhang, Q., & Yang, Y. (2019). Coupled estimation of 500 m and 8-day resolution global evapotranspiration and gross primary production in 2002–2017. *Remote Sensing of Environment*, *222*(January), 165–182. https://doi.org/10.1016/j.rse.2018.12.031

Zhou, R., Wang, H., Duan, K., & Liu, B. (2021). Diverse responses of vegetation to hydroclimate across temporal scales in a humid subtropical region. *Jounral of Hydrology: Regional Studies*, *33*, 100775. https://doi.org/10.1016/j.ejrh.2021.100775