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Characteristics of climatic trends and correlation between pan-evaporation and environmental factors in the last 40 years over China

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Abstract **Using the data observed by 62 Chinese Routine Meteorological Stations (CRMS) with long term radiation observation, the climatic trends and the relationship between pan-evaporation and its environmental factors are analyzed comprehensively. The results show that during the last 40 years, the relative humidity is uptrend in west China, downtrend in east China, and their extrema are 0.20%/a and –0.22%/a respectively; the precipitations of about 61% CRMS keep uptrend, its maximum can reach 10.52 mm/a^2 while the cloud amounts of about 79% CRMS keep downtrend slightly. About 98% CRMS display the air temperature uptrend, and the maximum is 0.11℃/a. About 76% CRMS display the land surface temperature uptrend. About 87% CRMS show the daily range of temperature downtrend. The global radiations observed by about 85% CRMS and the 10 m wind speeds observed by about 77% CRMS hold downtrend. The annual pan-evaporations of about 66% CRMS hold descend trend, and the biggest descent reaches –24.9 mm/a^2. The pan-evaporation has good relationship with many environmental factors, but the relationship with the relative humidity is the best. All of the climatic trends respond to the global climate changes.**

Keywords: climate change, pan, pan-evaporation, trend, environmental factor.

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One expected consequence of the global warming is that the air near surface should be dryer, which should result in an increase in the rate of evaporation from terrestrial open water bodies, and this increase should induce a series of changes in water circulation[1–4]. However, observations show that the regional-averaged pan-evaporation over some districts has a steady descent trend recently[1,5–13]. This phenomenon is far from people's expectation, and is known as the pan-evaporation paradox[6]. In 1995, Peterson et al.[5] reported a stable descent trend in pan-evaporation based on data from the United States and the former Soviet Union from 1950 to 1990, and attributed the decrease to the increment of cloud cover. In 1998, Brutsaert and Parlange[6] pointed out that it was the increase of the ground evaporation that resulted in the reduction of pan-evaporation, taking the difference of ground evaporation from pan-evaporation into consideration. In 2002, Roderick and Farquar[7] raised a query to the two review points above, and argued that the decline of total solar radiation was the main reason for the decreasing pan-evaporation by their further researches. Cohen and Stanhil[8,9] thought the increments of cloudiness and aerosol are the main factors that reduced the global solar radiation in recent years. In 2002, Ohmura and Wild[1] reviewed the study on pan-evaporation, and reported that there are a lot of disputes about this study. They pointed out some important aspects in further research work, especially the trend of actual evaporation from earth surface. They also thought that variety of evaporation is not decided only by the temperature; the trend of pan-evaporation is just a clue for cognition about actual evaporation; and we must pay much attention to the correlation/difference among pan-evaporation, evaporation from water surface, potential evaporation and actual evaporation from land surface and ocean surface, and the relationship between the global radiation and pan-evaporation in recent 10 years.

In this paper, we try to synthetically analyze the trend of meteorological elements of relative humidity, total amount of cloud, air temperature, soil surface temperature, diurnal temperature range, global solar radiation and wind speed observed by 62 CRMS with long-term radiation observation in the last 40 years for exploring their responses to the global climate changes, and study the correlation between pan-evaporation and meteorological factors. These analyses may be important for the study on forecast of climate change in our country.

1 Description of data

The dataset used in this research is observed by 62 CRMS with long-term radiation observation from 1961 to 2000. The dataset includes annual evaporation (accuracy, 0.1 mm, the same in the following), yearly-averaged global radiation (0.01 MJ/m^2), annual precipitation (0.1 mm), yearly-averaged total amount of cloud (10%), yearly-averaged wind speed at 10 m (0.1 m/s), yearly-averaged air temperature at 1.5 m (screen, 0.1℃), yearly-averaged diurnal temperature range (0.1℃), yearly-averaged relative humidity (1.0%), and yearly-averaged soil surface temperature (0.1℃)[14]. One can get the detailed information about observation instruments and averaging methods from ref. [14].

2 Analysis results

2.1 Trends of meteorological elements in the last 40 years

The studies of climate change mostly concentrated on air temperature, precipitation and disaster of drought/flood, etc.[15,16], neglecting other meteorological elements in our country. It is necessary to analyze variety of more meteorological elements for understanding climate change fully in our country. The trends of meteorological elements observed at 62 CRMS in the last 40 years are plotted in Fig. 1(a)—(h) corresponding to relative humidity, precipitation, total amount of cloud, air temperature, soil surface temperature, diurnal temperature range, wind speed and global radiation respectively. In Fig. 1, the black and solid triangles stand for uptrend, their size proportions to the magnitude of the uptrend, while the black and hollow ones for downtrend. Their statistical attributes are listed in Table 1.

Fig. 1 displays that the trends of relative humidity and precipitation go up in northwest China, which is consistent with the research about climatic transformation in northwest China[17−19]. But relative humidity has a downtrend in the east China, and precipitation still has an uptrend at the coastal areas in southeast China. On the average of all stations, the trend of relative humidity has a downtrend, with 66% CRMS having a downtrend and its maximum being –0.22%/a; the trend of precipitation is ascending, with 61% CRMS having an uptrend and its maximum being 10.52 mm/a^2. The total amount of cloud decreases. The air temperature rises almost over the country, 98% CRMS have an uptrend, its maximum is 0.11℃/a. The soil surface temperature has an uptrend in the most part of the country while it has a downtrend at the coastal areas in southeast China. The averaged diurnal temperature range has a downtrend. The global radiation and wind speed also have a falling trend on the average. Although the trends of the meteorological elements displayed in Fig. 1 and Table 1 are responses to the global climate changes, it is difficult to distinguish any causal relations among them.

Table 1 Trends of climatic change in the last 40 years in China

Physical quantity	Rang of trends	Percentage of uptrend (%)	Percentage of down-trend (%)
Potential evaporation	–24.91—10.44 mm/a^2	34	66
Relative humidity	–0.22—0.20 %/a	34	66
Precipitation	–9.02—10.52 mm/a^2	61	39
Total amount of cloud	–0.036—0.016 10%/a	21	79
Air temperature	–0.0017—0.11℃/a	98	2
Soil surface temperature	–0.041—0.076℃/a	76	24
Diurnal temperature range	~0.098—0.041℃/a	13	87
Total solar radiation	–37.70—21.52 MJ/m^2/a^2	15	85
Wind speed at 10 m	–0.056—0.025 m/s/a	23	77

2.2 Trend of pan-evaporation

Fig. 2 is the distribution of averaged pan-evaporation of 40 years observed by 62 CRMS during 1961—2000. To some extent, it reflects the air comprehensive dryness. The pan-evaporation over arid region is much greater than that over damp region.

Fig. 3 gives the trends of pan-evaporation observed at 62 CRMS from 1961 to 2000, and its symbols are the same as Fig. 1. By analyses of Fig. 1, there are 41 CRMS (about 66%) pan-evaporations having a downtrend with maximum of –24.9 mm/a^2; 21 CRMS (about 34%) having an uptrend with the maximum of 10.44 mm/a^2. So the pan-evaporation on the average has a downtrend. Fig. 4 shows two examples. Ürümqi station (CRMS number is 51463) has a larger downtrend; Shantou station (CRMS number is 59316) has a more obvious uptrend.

2.3 Definition of pan-evaporation and theoretical analyses about its relation with meteorological elements

Measuring evaporation with an evaporation-pan, and the evaporation-pan is in the same conditions as the ground surface, but the only difference is that the soil surface is set up by a unified, limited and special water surface artificially. Because the evaporation-pan is small and the atmospheric environment is open, its influence on the atmospheric environment is negligible. So the pan-evaporation is only the evaporation of limited water surface, not the actual evaporation from soil surface. It is the maximum evaporation, and the representation of potential evaporation from the soil surface, called potential evaporation. It is very different from the actual evaporation in physical concept. The actual evaporation (E) can be parameterized by the gradient transfer theory,

$$E = -\rho C_D (U - U_s)(e_{suf} - e), \tag{1}$$

where, ρ is air density, U and U_s are the wind speed and underlying surface moving speed separately, U_s is zero over land surface, e is air vapor pressure at reference height, e_{suf} is air vapor pressure on soil surface, and C_D is the drag coefficient, which is a function of surface roughness length, friction velocity and atmospheric thermal stratification stability[20]. e_{suf} is the real vapor pressure when calculating the actual evaporation from soil surface with eq. (1). But when calculating the potential evaporation, soil surface is set up by special water surface, so the vapor pressure equals the saturated vapor pressure, namely e_{suf}=e_s, and the difference between e_{suf} and e is the departure of air vapor from the saturated air. Saturated vapor pressure is a function of temperature,

$$e_s = e_0 \exp\left\{\frac{L_v}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right\}, \tag{2}$$

here T is the absolute temperature, T_0=273.15 K, L_v the latent heat constant, R_v the vapor gas constant, e_0 the saturated vapor pressure at T_0. Eq. (2) expresses that saturated vapor pressure is rising with temperature. The potential evaporation (E_{pan}) is a function of the relative humidity,

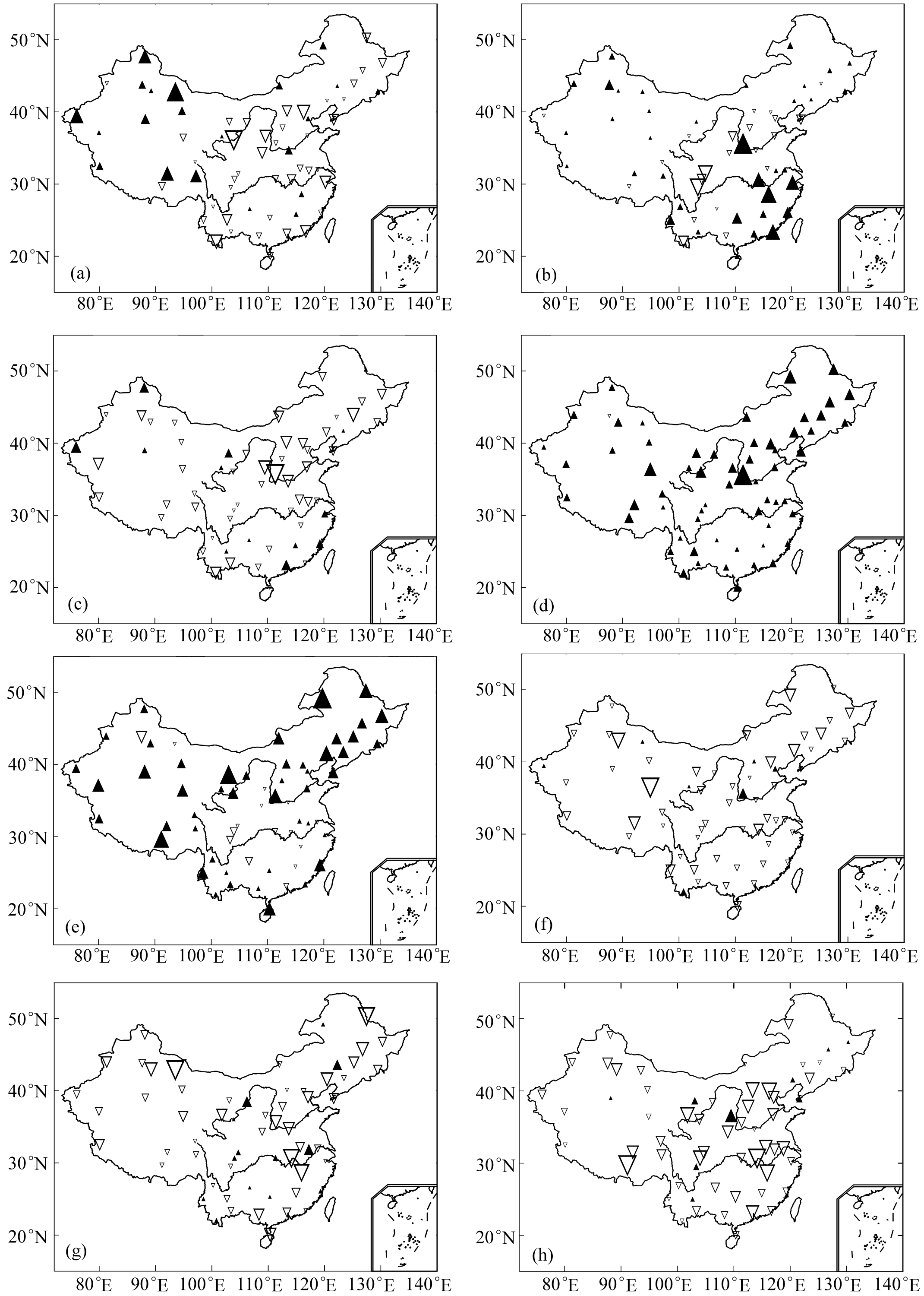

Fig. 1. The variety trends of relative humidity (a), precipitation (b), total cloudy amount (c), air temperature (d), surface temperature (e), daily range of temperature (f), wind speed at 10 m (g), total solar radiation (h) in the last 40 years in China. ▲ represents the uptrend; ▽ represents the downtrend; and the size of triangles is proportional to the range of variety.

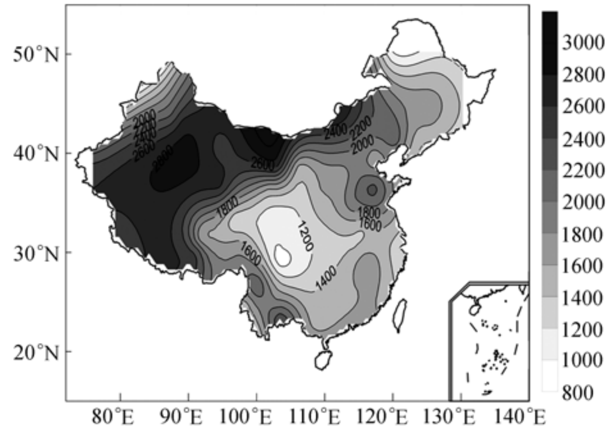

Fig. 2. Distribution of averaged pan-evaporation of 40 years.

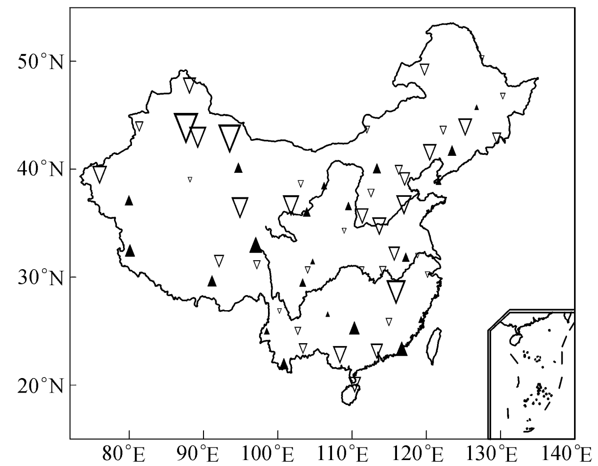

Fig. 3. Trends of pan-evaporation at 62 CRMS in the last 40 years.

$$E_{pan} = -\rho C_D U e_s (1 - f). \qquad (3)$$

Eqs. (2) and (3) indicate that the potential evaporation is a decreasing function with relative humidity, increasing with temperature, wind speed, saturated vapor pressure and drag coefficient. The more important thing is that the potential evaporation is determined with many meteorological factors, and the relations among them are not simple causal relations, some of them are implicit, even more, some meteorological factors interact on each other in some way. For example, the stronger global radiation will lead to the more unstable atmospheric thermal stratification, which will benefit stronger turbulence to increase C_D and strengthen the turbulent transportation, so the potential evaporation is built up with the global radiation; Similarly cloud and precipitation will affect the potential evaporation, and the increments of total amount of cloud and precipitation decrease the potential evaporation through restraining turbulent transportation by reducing, radiation heat on soil surface. For instance, on one hand the wind can blow quickly the water vapor off evaporation-pan to strengthen evaporation, on the other hand, the wind can make advection greater, and the wet and cold advection can decrease the potential evaporation. So we can see that the potential evaporation is a very complex and nonlinear function of relative humidity, temperature, global radiation, wind speed, etc., and reflects the synthesis effect of many meteorological elements. The synthesis effect of many meteorological elements produce the bulk trend of the potential evaporation displayed in Fig. 3, Fig. 4 and Table 1 during the last 40 years in our country.

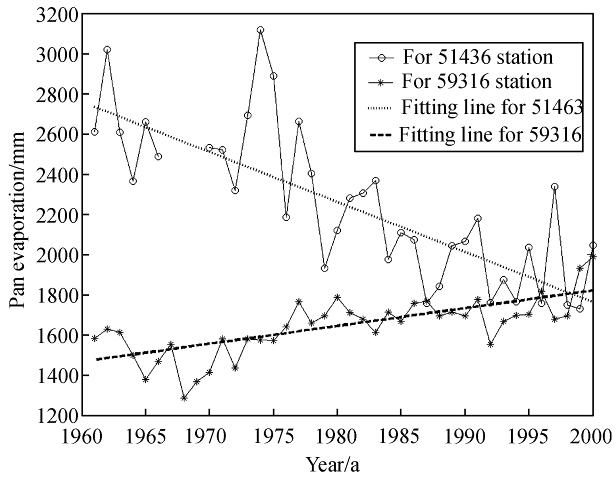

Fig. 4. Trend of pan-evaporation of Urumqi and Shantou in the last 40 years.

2.4 Linear correlation analyses between observed potential evaporation and meteorological factors

To have a comprehensive understanding of the complicated relation between evaporation potential and each meteorological factor, their correlation was analyzed. Their statistics features are listed in Table 2. Table 2 shows that the potential evaporation has correlation with many meteorological factors and the characteristics of their correlation coefficients vary with areas. The correlation between the potential evaporation and relative humidity is the best, and all correlations are negative with 90% CRMS passing α =0.05 confidence test. The correlations between the potential evaporation with precipitation and total amount of cloud that pass α =0.05 confidence test are 76% and 50% separately, and they are all negative. The correlations between the potential evaporation with air temperature, diurnal temperature range and soil surface temperature that pass α =0.05 confidence test are 66%, 74% and 73% separately, but they vary with regions. The averaged correlations are positive because of the positive correlations taking advantage. The correlations between the potential evaporation with global radiation, and wind speed at 10 m height that pass α =0.05 confidence test are 65% and 73% separately, but they also vary with regions. These analyses express that the potential evaporation is decided by many factors, which are consistent with the theoretical analyses in Section 2.3.

Table 2 Statistic analysis of correlation coefficients between the potential evaporation and meteorological factors

Factor	Percentage of passing α =0.05 confidence test	Biggest positive correlation	Biggest negative correlation	Averaged correlation coefficient
Relative humidity	90%	Non	−0.83	−0.53
Precipitation	76%	0.19	−0.77	−0.38
Total amount of cloud	50%	0.26	−0.69	−0.27
Air temperature	66%	0.65	−0.65	0.26
Global radiation	65%	0.82	−0.63	0.28
Wind speed	73%	0.87	−0.40	0.31
Soil surface temperature	73%	0.80	−0.55	0.34
Diurnal temperature range	74%	0.80	−0.69	0.35

2.5 Multiple correlation analyses between potential evaporation and meteorological elements

We try to explain influences of cloud, wind speed, relative humidity, precipitation, air temperature, diurnal temperature range, global radiation and soil surface temperature on the potential evaporation with multiple correlation analysis. The mean partial correlation coefficients are listed in Table 3. Table 3 shows that the best correlation is between the potential evaporation and relative humidity among 8 meteorological factors mentioned above, with its mean partial correlation coefficient being 0.964 while the worst one is between the potential evaporation and precipitation, with its mean partial correlation coefficient being only 0.63. These meteorological factors can be classified into three groups according to their characters, wet factor including cloud, relative humidity and precipitation, thermal factor including air temperature, soil surface temperature, diurnal temperature range, global radiation, and dynamic factor including wind. Fig. 5 gives the distributions of partial correlation coefficients of some representative factors (relative humidity, diurnal temperature range and wind speed).

Table 3 Mean partial and multiple correlation coefficients of multiple correlation analysis among the potential evaporation with meteorological factors in China

Meteorological elements	Cloudy	Wind speed	Relative humidity	Precipitation	Air temperature	Diurnal temperature range	Global radiation	Soil surface temperature	Multiple correlation coefficient
Coefficients	0.909	0.868	0.964	0.630	0.929	0.954	0.850	0.918	0.863

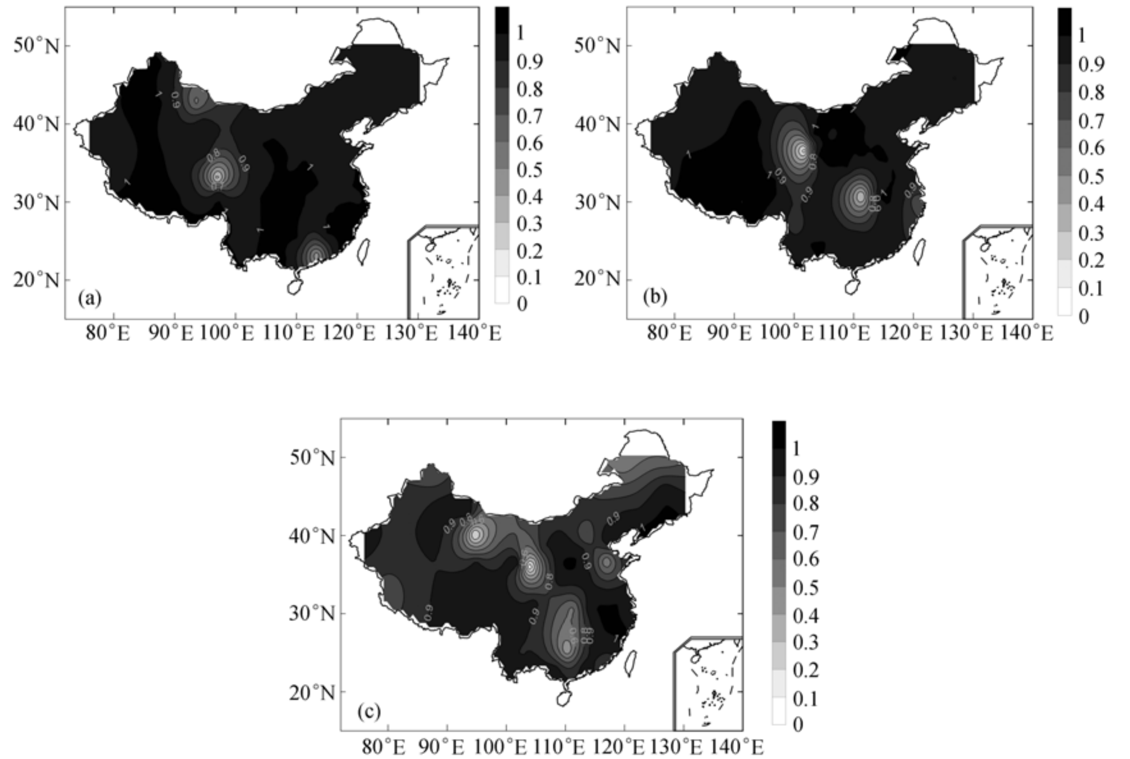

Fig. 5. Distribution of the partial correlation coefficients between the potential evaporation with relative humidity (a), diurnal temperature range (b) and wind speed (c).

Based on the analyses on the partial correlation coefficients between the potential evaporation and relative humidity (Fig. 5(a)), the most of partial correlation coefficients are very high (beyond 0.9) except that at Hami at the east of Xinjiang (0.56), Yushu in Qinghai-Tibet Plateau (0.21) and Guangzhou (0.41). There are three regions where relative humidity markedly influences the potential evaporation and their partial correlation coefficients are very close to 1.0. The first is the south-north belt region from the north of Xinjiang to the west of Tibet, the second is the south-north belt region from the south of the Great Bend of the Yellow River to the border land between Yunnan and Guangxi provinces, and the third is in Fujian Province. For the areas of Hami, Yushu and Guangzhou, the more important meteorological factors to the potential evaporation are diurnal temperature range, total amount of cloud and soil surface temperature. On the average, the precipitation has slighter influence on the potential evaporation (its diagram is omitted).

Diurnal temperature range, a thermal factor, is just next to relative humidity in meteorological factors that influence the potential evaporation (Fig. 5(b)). The partial correlation coefficients in the great majority of our country are over 0.90, especially in the east of Qinghai-Tibet Plateau and the Great Bend of the Yellow River. But there are still two stations (Xining and Yichang) at which the most important factor is not diurnal temperature range. For Xining in the east of Qinghai-Tibet Plateau, temperature has much more influence than diurnal temperature range while for Yichang at the middle reaches of the Yangtze River, relative humidity and air temperature are the more important factors on the potential evaporation.

Wind is the only dynamic factor in 8 meteorological elements. The global warming leads centers of atmospheric action and the westerly belt in the Northern Hemisphere to move northward[21], which makes the wind speed near surface weak, and causes the potential evaporation to decrease. According to the figure of the partial correlation coefficients between the potential evaporation and wind speed (Fig. 5(c)), there are three regions (Lanzhou, Dunhuang and Guilin) where wind speed has a very little correlation with the potential evaporation, implying wind has little effect on the potential evaporation, in other words, wind is not the key factor to the potential evaporation. Because these areas are located in basin/mountain areas, their averaged speeds are smaller, for example, the frequencies of static wind in Lanzhou and Dunhuang are 33% and 62% respectively. The key factors to influence the potential evaporation are temperature and corresponding factors that can influence temperature, such as total amount of cloud and global radiation.

According to the analyses above, one can easily understand the correlation between the potential evaporation and meteorological elements displayed in Table 2. The correlations of the potential evaporation with relative humidity, precipitation and total amount of cloud are negative, the correlations with temperature, global radiation and wind speed are positive, and there exist nonlinear correlations of evaporation potential with meteorological factors, like specific humidity, temperature global radiation, wind speed, etc. In fact, this is the physical cause that makes the characteristics of correlations change with regions. The observations displayed in Fig. 1 also prognosticate that there are some obvious trends of meteorological elements during the last 40 years, for example, air temperature has uptrend, diurnal temperature range downtrend, while total amount of cloud, global radiation and wind speed also has downtrend. The synthesis effect of theses meteorological elements produces the bulk trend of the potential evaporation displayed in Figs. 3 and 4 and Table 1 during the last 40 years in our country. So, the potential evaporation is a result produced by various environmental factors through nonlinear interactions, among which the departure of air water vapor from the saturated air is a predominant factor. Only considering certain single factor on the potential evaporation will produce some biases. For example, "The global warming will make the air near surface dryer, which should result in an increase in the rate of evaporation from terrestrial open water bodies. However, observations show that the regional-averaged pan-evaporation over some districts has a steady descent trend recently. This phenomenon is far from people's expectation, and is known as the pan-evaporation paradox. " All this in introduction is a kind of misunderstanding caused by only considering single environmental factor influencing evaporation.

3 Conclusions and discussions

Evaporation (transpiration) is not only an important constituent of surface energy balance, but also a key constituent of surface hydrology balance. It is the part affected directly by land-use and climate changes in surface hydrology balance. However, evaporation (transpiration) can adjust climate through decreasing transformation from radiation to sensible heat flux, increasing air humidity, increasing minimum temperature and decreasing maximum temperature. Furthermore, as one of the regular observations in hydrology and meteorology, the pan-evaporation is an important reference index of evaluating water resources to study hydrology, and design irrigation engineering and climatic division. Therefore, it is very meaningful for further understanding and studying the rules and causes of climate changes. From the above, the main conclusions are as follows:

(1) Analyses of observations in CRMS show that relative humidity is downtrend at 66% CRMS, its maximum is –0.22%/a, precipitation uptrend at 61% CRMS, its maximum 10.52 mm/a^2, total amount of cloud downtrend at 79% CRMS, air temperature uptrend at 98% CRMS, and its maximum 0.11℃/a, while diurnal temperature

range is downtrend at 87% CRMS, global radiation downtrend at 85% CRMS, wind speed downtrend at 77% CRMS. Meanwhile pan-evaporation has downtrend at 66% CRMS, and its maximum is –24.9 mm/a^2.

(2) Physical analyses express the potential evaporation has correlation with many meteorological elements. That the linear correlation coefficients between the potential evaporation and meteorological environmental factors vary with regions verifies the results of the physical analyses. The results of the multiple correlation analyses display that the potential evaporation is synthetical effects of many meteorological factors, and it has the best correlation with relative humidity. So it is hard to explain the potential evaporation change by using certain single environmental factor.

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