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Aridity/humidity status of land surface in China during the last three decades

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Abstract To clarify aridity/humidity status of land surface is helpful for studying environmental background and regional differences, seeking causes of environmental change, and providing a scientific basis for researches on climate change in the future. In this paper, the authors calculated potential evapotranspiration of China using data from 616 meteorological stations during the period of 1971—2000 with the Penman-Monteith model recommanded by FAO in 1998. Vysothkii's model was used to calculate aridity/humidity index. Then the calculated results of stations were interpolated to land surface using ArcGIS. Results show that the annual average potential evapotranspiration is 400—1500 mm in the whole country, 600—800 mm in most parts of it; and 350—1400 mm in growing season (April—Octobor), which is nearly 200 mm less than the annual average. According to the aridity/humidity indexes of 1.0, 1.5 and 4.0, the aridity/humidity status is categorized to four types, namely, humid, subhumid, semiarid and arid. A majority of stations (76%) are more humid in growing season than the annual average. Results of comprisons between the distribution map of aridity/humidity index with that of precipitation and vegetation indicate a good consistence of aridity/humidity status with natural environment. Therefore potential evapotranspiration calculated with modified FAO's Penman-Monteith model in combination with aridity/humidity index that considers water balance can more reasonably explain the actual land surface aridity/humidity status of China.

Keywords: potential evapotranspiration, aridity/humidity status, land surface, regional differences, Penman-Monteith.

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To understand regional status and differences is groundwork for researching environmental change, such as regional response to global change, land use/land-cover change, land desertification, and sand/dust storms. At present, geographers are searching for driving forces of environmental change and making efforts to reflect human actions on these changes[1−4]. To recognize regional difference, most researches focus on single factor, such as temperature, precipitation, soil and vegetation. However, nature is an open system and natural factors are in a state of interaction. The difference of single factor cannot reflect regional differences and certainly cannot explain causes of environmental changes. Therefore, it is important to seek integrated natural factors to explain regional differences. In order to distinguish from human actions, natural factors should have three features: (1) human cannot change them to a great degree at present; (2) it is possible for them to have a notable change in a short period; and (3) their changes can cause a series of environmental changes. Temperature, precipitation, solar radiation, and wind are such natural factors. These factors synthetically influence aridity/humidity status expressed by precipitation and potential evapotranspiration. According to IPCC studies, 30 years can be a basic scenario period to reflect current climate status[5]. The years 1971—2000 are a period that China has systematic weather records, thus we take it as a basic study period.

Studies of aridity/humidity status have been focused on how to determine potential evapotranspiration, which is denoted as ET_o, and aridity/humidity index of a region[6,7]. There are many definitions on ET_o that make it confused to be understood and compared[8,9]. ET_o is the evaporative demand of the atmosphere independent of crop type, crop development and management practices[10]. Since ET_o is difficult to measure, it is usually estimated by models[11,12], such as Penman, Thornthwaite and Selianinov models.

Many Chinese scientists have studied aridity/humidity status of China using a variety of models or modified empirical coefficients to fit natural conditions in China[13−20]. The original models were established in specified environments. For example, in Selianinov's model, the hypothesis of cumulated temperature during ≥10℃ days standing for certain ET_o is empirical, because living things are still alive and have activities when temperature is lower than 10℃, and precipitation retained in soil at the moment can be utilized in the coming warmer season[21]. Moreover, natural environment of China is diverse and complicated; it is thus difficult to apply such models developed under homogeneous conditions to China. Seeking a suitable model recognized worldwide to study the aridity/humidity status of China is the focus of this study.

Penman's combination model, integrating mass transfer and energy balance, and taking into consideration many influencing factors such as temperature, sunshine, relative humidity and wind speed, has been widely applied and modified[22−25]. The modification by Monteith in particular considered vegetation physiological characters and introduced the concept of surface resistance[26]. The relatively accurate and consistent performance of Penman-Monteith model (P-M model in abbreviation) in both arid and humid climates has been demonstrated by the American Society of Civil Engineers (ASCE) based on comparing with about twenty models[11]. Similar conclusions were also obtained in EU researches[27].

In 1998, FAO modified P-M model again, which defined a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 to calculate ET_o. The reference crops closely resemble the evapotranspiration of an extension surface of green grass of uniform height, actively growing, completely shading the ground and adequately watered[12]. In 2000, ASCE applied the same hypothetical surface to standardizing the calculation of ET_o. Such hypothesis has a similar mechanism with land surface evapotranspiration, which avoids climatically irrelevant factors such as vegetation type, height and growth status. It makes sure that ET_o is only a function of climate, and increases comparability among regions and periods. FAO's P-M model has proved to have a global validity as a standardized reference for potential evapotranspiration, and it can be applied in regions with different environmental conditions[27]. FAO's P-M model, which meets the requirements of this study, is used to calculate nationwide ET_o and then convert to aridity/humidity index for analysis of aridity/humidity status of China during the last three decades.

1 Data and model

1.1 Data

Climatic data used in this paper were provided by Climatic Data Center of China Meteorological Administration, including daily data of precipitation, wind speed, relative humidity, sunshine hours, and monthly data of the minimum and the maximum temperature of 616 meteorological stations during the period from January 1, 1971 to December 31, 2000. Longitude, latitude and altitude above sea level were also included. The meteorological data of the 616 stations have complete records available for calculating ET_o.

1.2 Potential evapotranspiration

P-M model recommended by FAO in 1998 was applied to calculating ET_o:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1+0.34U_2)},$$

where R_n is net radiation: $R_n = R_{ns} - R_{nl}$;

R_{ns}—net shortwave radiation:

$$R_{ns} = (1-\alpha)\left(a + b\frac{n}{N}\right)R_a;$$

R_{nl}—net longwave radiation:

$$R_{nl} = \sigma\left[\frac{T^4_{max,k} + T^4_{min,k}}{2}\right]\left(c - d\sqrt{e_a}\right)\left(e\frac{R_s}{R_{so}} - f\right);$$

where σ is Stefan-Boltzmann's constant (4.903×10^{-9} MJ $K^{-4}m^{-2}day^{-1}$), T_k is Kelvin temperature (K =℃+ 273.16).

Net radiation is the base for calculation of P-M model, and it is usually obtained by calculation, the focus of which is to determine the empirical coefficients. FAO suggests the values of a=0.25, b=0.50, c=0.34, d=0.14, e=1.35, and f=0.35 when there is no regional reversion. Zuo Dakang obtained a=0.248 and b=0.752 based on observations of total radiation, percentage of monthly sunshine hours and monthly clear-sky total radiation in China[28]. Wang Yixian applied Zuo's coefficients and Penman's energy balance model to calculating R_{ns}[29]. Wang's results fit China's status and have been widely applied[9, 30]. The present study also uses Wang's empirical coefficients in the net radiation formula:

$$R_{ns} = (1-0.23)(0.248 + 0.752n/N)R_{so},$$

$$R_{nl} = \sigma\left[\frac{T^4_{max,k} + T^4_{min,k}}{2}\right](0.56 - 0.08\sqrt{e_a})(0.1 + 0.9n/N).$$

The remaining coefficients were calculated using FAO's suggestion as the following:

P (kP$_a$)—atmospheric pressure:

$$P = 101.3\left(\frac{293 - 0.0065h}{293}\right)^{5.26} \text{ (}h\text{ is elevation a.s.l.(m))},$$

λ (MJ/kg)—latent heat of vaporization: λ= 2.501 –0.002361T, γ(kP$_a$/℃)—psychrometric constant: $\gamma=C_pP/\varepsilon\lambda=0.000665P$; where C_p is specific heat at constant pressure (1.013×10^{-3} MJ/kg·℃), ε is ratio of molecular weight of water vapor/dry air (0.622). T_{mean}—mean temperature: $T_{mean}=(T_{max}+T_{min})/2$, $e°(T)$ (kP$_a$)—saturation vapor pressure: $e°(T)=0.6108\exp[17.27T/(T+237.3)]$.

This formula is nonlinear, therefore vapor pressure of a certain period should be the arithmetic mean of the vapor pressure at the maximum and the minimum air temperatures in the same period: $e_s=[e°(T_{max})+e°(T_{min})]/2$.

Δ(kP$_a$/℃)—slope of saturation vapor pressure curve:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T_{mean}}{T_{mean}+237.3}\right)\right]}{(T_{mean}+237.3)^2},$$

e_a(kP$_a$)—actual vapor pressure:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e°(T_{max}) + e°(T_{min})}{2}\right].$$

For solar radiation, calculation of net radiation requires extraterrestrial radiation R_a (MJ/m^2·d), albedo α (0.23), actual duration of sunshine n (hour), and the maximum possible duration of sunshine or daylight hours N (hour).

R_a was calculated with solar constant G_{sc} (0.082 MJ/m^2·min), relative distance between Earth and Sun d_r, sunset angle ω (rad), latitude ψ (rad, positive in the northern hemisphere), solar declination δ (rad), and number of days J (for January 1, J=1; for December 31, J=365 or 366):

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)],$$

where $d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right)$, $\delta = 0.409\sin\cdot\left(\frac{2\pi}{365}J - 1.39\right)$, ω_s=arccos[−tan(φ)tan(δ)].

R_{so} — clear-sky solar radiation: $R_{so}=(0.75+2\times10^{-5}h)R_a$;

N—daylight hours: $N=24\cdot\omega_s/\pi$.

Soil heat flux G is small compared with net radiation, therefore "$G = 0$" was assumed in many models. In FAO's P-M model it is calculated with a simple formula: $G_{month,i} = 0.14(T_{month,i} - T_{month,i-1})$, where $T_{month,i}$ is the mean temperature of the ith month, $T_{month,i-1}$ is the mean temperature of the previous month.

According to FAO's formula, wind speed observed at 10 m height (U_{10}, m/s) was updated to wind speed at 2 m (U_2, m/s): $U_2=4.87U_{10}/\ln(67.8\times10-5.42)=0.75U_{10}$.

1.3 Aridity/humidity index

Aridity/humidity index is used to express drought level of a region. In this study, after calculating ET_o of China for the last three decades, aridity/humidity index (I_a) was defined as reciprocal of Vysotskii's humidity coefficient1):

$$I_a = ET_o / P.$$

Corresponding to Vysotskii's humidity coefficient, I_a was classified as: $I_a < 1.00$ is humid; $1.00 \le I_a < 1.50$ is subhumid; $1.50 \le I_a < 4.00$ is semiarid and $I_a \ge 4.00$ is arid.

2 Aridity/humidity status of land surface in China during 1971—2000

Based on the meteorological data and FAO's P-M model, potential evapotranspiration and aridity/humidity index of China in the last three decades were calculated. Results of some stations are listed in Table 1. Interpolation by ArcGIS software generates the distribution maps of the annual average potential evapotranspiration (Fig. 1) and in growing season in China.

The results show that the annual average potential evapotranspiration is 400—1500 mm in the whole country, and 500—1200 mm in most parts of the country. Northeast China and Tianshan Mountains are two low value regions. It is 600—800 mm in the western part of Northeast China and Central China, the eastern part of the Tibetan Plateau, Tacheng and Altay mountainous regions; 800—1000 mm in North China, East China, South China, western part of the Tibetan Plateau, and most part of Northwest China; and 1000–1200 mm in areas from the Tarim Basin to the Qaidam Basin, Ejin to Erenhot, dry valleys of Hengduan Mountains, east coastal areas and hinterland of the Tibetan Plateau, which are high value regions. It even exceeds 1200 mm in some regions, such as Ejin, parts of dry valleys of Hengduan Mountains and western part of Hainan Island.

By comparing the present calculation results with the former similar studies, the changing range of the country's potential evapotranspiration show a slight difference, for example 700—1300 mm[9] and 500—1200 mm[31]. ET_o of different studies is almost the same in eastern China, but it is quite different in western China and the Tibetan Plateau because of sparse meteorological stations and effect of varying topographic factors. It is inevitable that differences exist and may contribute to the period for data collected, different calculation models and influence of climate change, but the effect of climate change on the change of potential evapotranspiration and its regional difference need further studies.

During growing season (April—October) ET_o is 350—1400 mm, and in most parts of China it is 600—1000 mm. Compared with the annual value, it is about 200 mm less, and the high and low values distribution is similar. However, in East China, North China and

1) Vysotskii's model: $K=P/E_o$, K=humidity coefficient, P=precipitation, E_o=potential evapotranspiration.

Table 1 Calculation results of some meteorological stations

Station	Series No.	Province & Autonomous Regions	Longitude (°E)	Latitude (°N)	Altitude /m	Annual			Growing season			①	②	③
						P/mm	ET_o/mm	I_a	P/mm	ET_o/mm	I_a			
Yangjiang	59663	Guangdong	111.97	21.87	23.3	2443.2	1003.6	0.41	2179.8	705.8	0.32	89.2	70.3	18.9
Pucheng	58731	Fujian	118.53	27.92	276.9	1700.7	829.0	0.49	1242.4	660.5	0.53	73.1	79.7	-6.6
Danxian	59845	Hainan	109.58	19.52	168.7	1850.0	1102.2	0.60	1662.0	792.4	0.48	89.8	71.9	17.9
Luzhou	57602	Sichuan	105.43	28.88	334.8	1094.0	715.2	0.65	928.4	577.5	0.62	84.9	80.7	4.2
Xinyang	57297	Henan	114.05	32.13	114.5	1106.1	824.7	0.75	892.6	664.1	0.74	80.7	80.5	0.2
Jiaohe	54181	Jilin	127.33	43.70	295.0	676.8	594.4	0.88	621.3	534.1	0.86	91.8	89.8	2.0
Ganyu	58040	Jiangsu	119.12	34.83	2.1	906.3	827.7	0.91	789.1	673.4	0.85	87.1	81.4	5.7
Daofu	56167	Sichuan	101.12	30.98	2957.2	618.0	787.1	1.27	596.8	609.2	1.02	96.6	77.4	19.2
Wugong	57034	Shaanxi	108.22	34.25	447.8	572.0	732.6	1.28	501.6	609.9	1.22	87.7	83.3	4.4
Chengde	54423	Hebei	117.93	40.97	377.2	512.2	672.3	1.31	487.8	600.9	1.23	95.2	89.4	5.8
Yushu	56029	Qinghai	97.02	33.02	3681.2	485.9	677.0	1.39	463.4	544.2	1.17	95.4	80.4	15.0
Yan'an	53845	Shaanxi	109.50	36.60	957.8	510.8	770.9	1.51	468.3	643.9	1.38	91.7	83.5	8.2
Xiji	53903	Ningxia	105.72	35.97	1916.5	398.1	683.6	1.72	372.8	571.2	1.53	93.6	83.6	10.1
Yuzhong	52983	Gansu	104.15	35.87	1874.1	381.8	703.7	1.84	358.4	599.5	1.67	93.9	85.2	8.7
Hohhot	53463	Inner Mongolia	111.68	40.82	1063.0	398.0	756.4	1.90	372.1	672.2	1.81	93.5	88.9	4.6
Baotou	53446	Inner Mongolia	109.85	40.67	1067.2	297.7	883.5	2.97	278.3	770.0	2.77	93.5	87.2	6.3
Tongxin	53810	Ningxia	105.90	36.98	1343.9	267.8	975.1	3.64	249.0	821.0	3.30	93.0	84.2	8.8
Wuwei	52679	Gansu	102.67	37.92	1530.9	165.9	778.9	4.70	151.3	667.4	4.41	91.2	85.7	5.5
Sonid Zuo	53195	Inner Mongolia	113.72	43.83	1111.4	185.2	926.9	5.00	172.5	851.4	4.94	93.1	91.9	1.3
Kash	51709	Xinjiang	75.98	39.47	1288.7	64.1	892.0	13.92	46.2	797.6	17.27	72.1	89.4	–17.3
Golmud	52818	Qinghai	94.90	36.42	2807.6	42.1	985.9	23.42	38.6	823.4	21.34	91.7	83.5	8.2
Dunhuang	52418	Gansu	94.68	40.15	1139.0	42.2	944.8	22.37	36.5	817.0	22.38	86.4	86.5	0.1
Turpan	51573	Xinjiang	89.20	42.93	34.5	15.7	858.4	54.85	11.4	805.8	70.81	72.7	93.9	–21.2

① Percentage of precipitation in growing season to annual; ② percentage of potential evapotranspiration in growing season to annual; ③ difference of the two columns, negative value indicating dryer status in growing season.

coastal areas ET_o shows much difference and is about 600—800 mm. Results indicate that most stations (76%) are more humid in growing season than that of the whole year. The reasons could be the monsoon climate in China with higher temperature and concentrated precipitation during growing season. When temperature plays a greater role in ET_o during growing season it will cause dryer status.

Aridity/humidity index was interpolated and classified to demonstrate its distribution over China (Fig. 2). The map shows that the vast areas to the eastern part of the Tibetan Plateau, southern piedmont of Qinling Mountains, southern part of the Huaihe River plain, and eastern part of Northeast China are humid regions; the western part of Northeast China, the lower reaches of the Yellow River plain and the southeastern part of the Tibetan Plateau are subhumid regions; most part of the North China Plain, the Loess Plateau, eastern part of the Inner Mongolia Plateau, northeastern to central and western parts of the Tibetan Plateau, and Tianshan Mountains are semiarid regions; and areas west of Sonid Zuoqi to Erenhot, Ejin, most part of Xinjiang and the northwestern of the Tibetan Plateau are arid regions. The status of growing season is generally similar except that the scopes of humid and subhumid regions in the southeastern part of the Tibetan Plateau and subhumid regions in North China Plain are much wider.

3 Result validity

Aridity/humidity status represented by potential evapotranspiration and precipitation was compared with actual environments to check its validity. Usually regions with annual precipitation exceeding 800 mm are regarded as humid regions, 400—800 mm as subhumid regions, 200—400 mm as semiarid regions, and less than 200 mm as arid regions[32]. Vegetation distribution can also reflect a variety of environmental

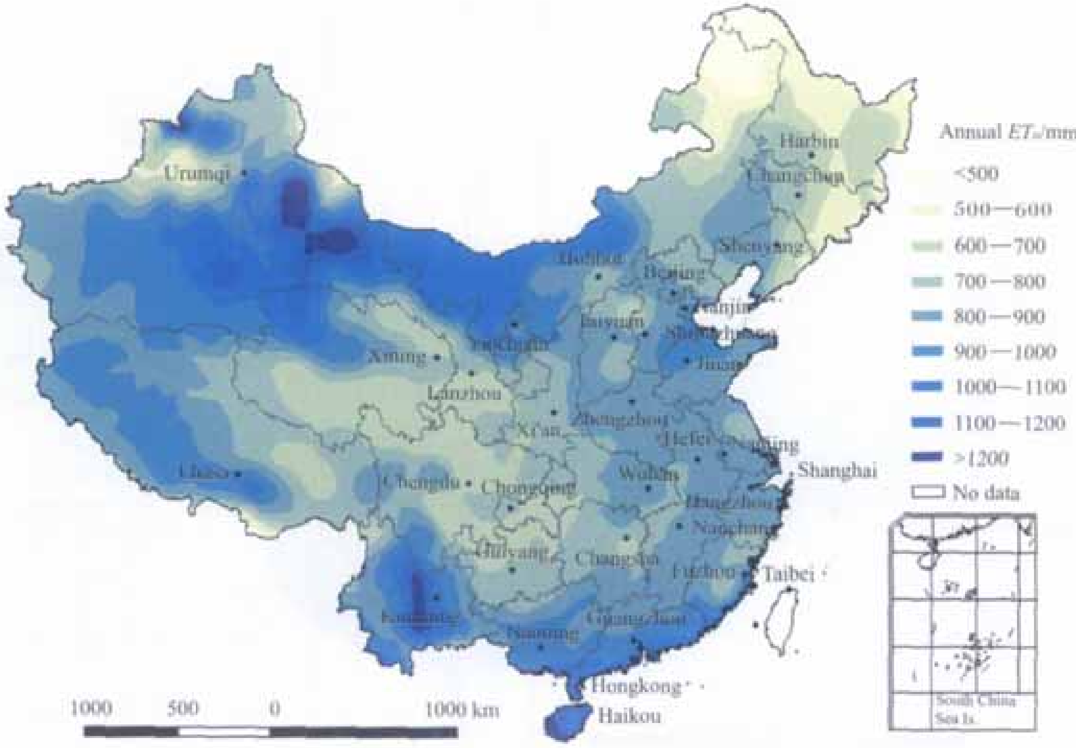

Fig. 1. Potential evapotranspiration in China during 1971—2000.

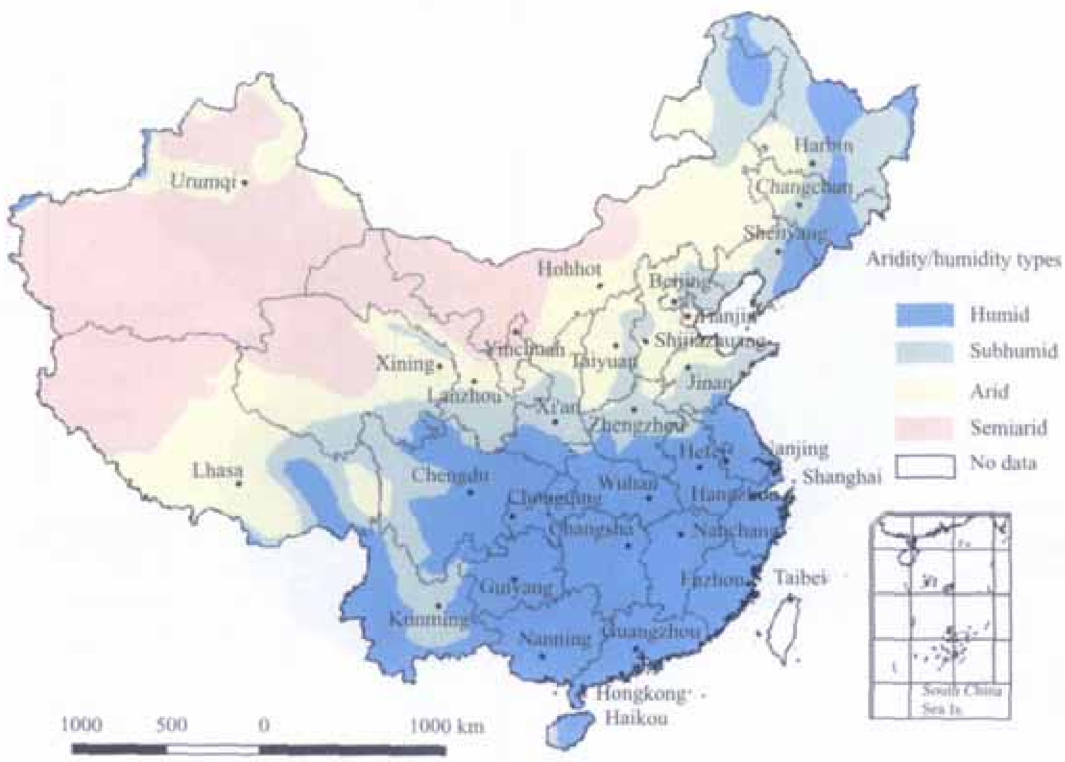

Fig. 2. Annual aridity/humidity types in China during 1971—2000.

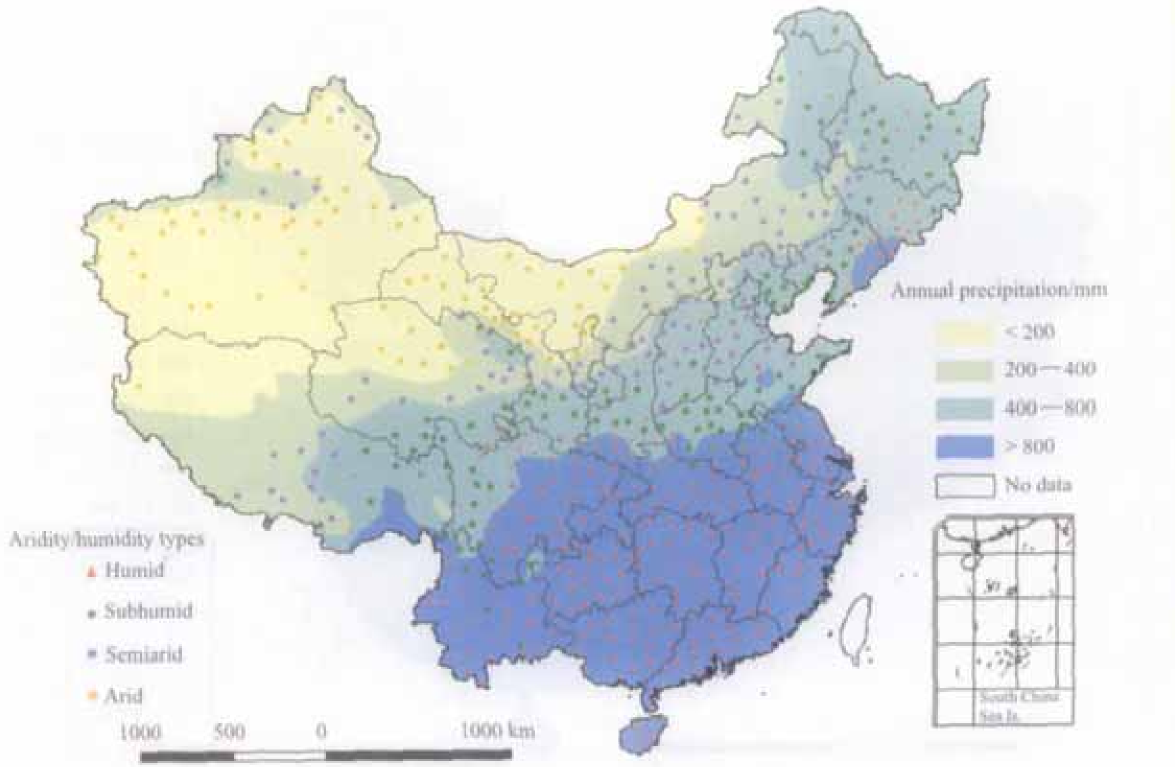

Fig. 3. Comparisons between aridity/humidity types of meteorological stations and precipitation.

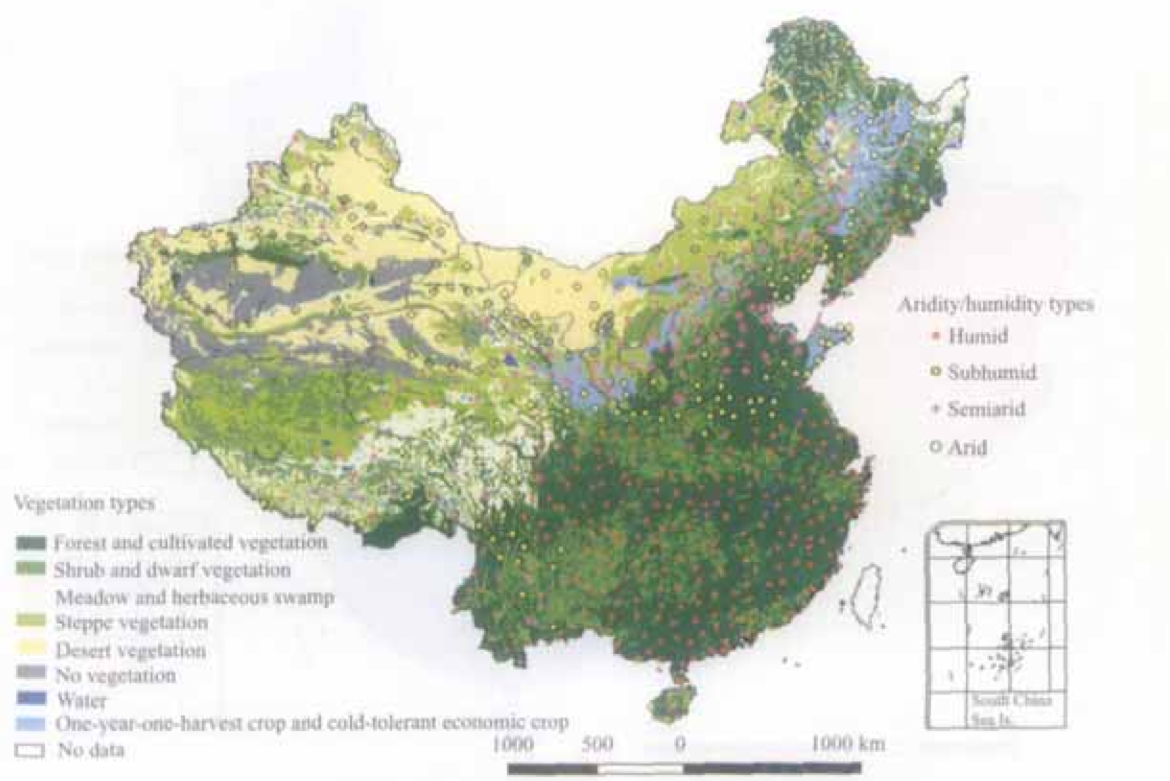

Fig. 4. Comparisons between aridity/humidity types of meteorological stations and vegetation types.

Table 2 Comparisons of aridity/humidity types of the stations with precipitation and vegetation

Types	No. of stations		Comparison with precipitation				Comparison with vegetation			
	A	GS	A	HR	GS	HR	A	HR	GS	HR
Humid	284	318	252	89%	228	72%	269	95%	293	92%
Subhumid	116	117	105	91%	108	92%	57	49%	51	44%
Semiarid	138	99	66	49%	70	70%	30	22%	21	20%
Arid	79	83	72	91%	83	100%	29	37%	29	35%

A=Annual; GS=Growing season; HR=Homogeneous rate.

factors, especially water and heat conditions. Generally in China, forest and cultivated vegetation are considered as humid, shrub and dwarf vegetation as humid/subhumid, steppe vegetation as semiarid, and desert vegetation and no vegetation as arid. Aridity/humidity indexes of the stations were compared with annual precipitation and vegetation distribution of China to valid the calculation results (Table 2, Figs. 3 and 4).

Table 2 shows that aridity/humidity types of most stations match well to the precipitation classes and vegetation types, especially in humid and arid regions. Homogeneous rate in subhumid and semiarid regions are not so good because of uncertainty in such transitional zones.

4 Conclusion and prospect

Aridity/humidity status of land surface, which was expressed by potential evapotranspiration and aridity/humidity index, considers multiple meteorological factors. Based on calculation of the modified FAO's P-M model, the annual average potential evapotranspiration is 400—1500 mm and 350—1400 mm in growing season in China during the years of 1971—2000. Aridity/humidity index was compared with the traditional moisture indicators, i.e. precipitation and vegetation types. Good consistency shows that FAO's P-M model can be applied to China with local modification of radiation part. However, because of much uncertainty in subhumid and semiarid regions, further detailed studies are needed. It would be more favorable for analyzing aridity/humidity status in the whole China where natural environment is diversified by using a more suitable model for regional comparisons.

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