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Seasonal and Spatial Variation of Evapotranspiration in the Mountains of Southwest China

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Abstract: Estimations of potential evapotranspiration (*PET*) were calculated according to a modified Penman formula for 36 meteorological observatories in the mountains of Southwest China, particularly in Yunnan Province. Based on these data stations were grouped in climatically homogenous regions (climate provinces) and the mean monthly *PET* lapse rate for each climate province was calculated. The seasonal distribution of climate provinces reflects the varying degree of influence of the monsoonal air masses. The intraannual variation of *PET* can be divided into three seasons (premonsoon, monsoon and postmonsoon). Regional monthly lapse rates vary mainly between −1 mm/100 m and −5 mm/100 m. Positive lapse rates and inversions are assumed to result from local phenomena like ground fog or cloud layers inhibiting solar radiation at lower levels. The highest *PET* values and the largest spatial range of *PET* values occur during the premonsoon (February-May), due to large regional differences in solar radiation and wind speed. During the monsoon season (June-September) all parts of the region are under influence of the Southwest Monsoon leading to a homogenous climatic environment, low *PET* values and small spatial variations of *PET*.

Key words: Mountains of Southwest China; evapotranspiration; seasonal and spatial variation

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1 Introduction

Of all climatic elements potential evapotranspiration (*PET*) is the least well known. This is even more true for mountains: ten years ago Barry (1992) listed only two articles on *PET* estimates in mountain areas. Without doubt this is partly due to the difficulty of estimating *PET* which is difficult to measure directly like other climatic elements, but has to be derived from several sets of measurements which are usually only observed at meteorological observatories.

This paper presents estimates of long－term mean monthly *PET* rates for 36 meteorological observatories in the mountains of Southwest China, calculated according to a modified Penman equation. All *PET* estimates were used to delineate climatically homogenous regions, which are defined by *PET* values obeying a common vertical gradient. Monthly lapse rates for each region were calculated and the seasonal and spatial variation of *PET* is described.

2 Climatic Characteristics of the Southwest China Mountain Region

The Southwest China mountain region lies in the extreme Southwest of the PR China, bordering Myanmar, Laos and Vietnam (Fig. 1). It consists mainly of Yunnan Province and some parts of Sichuan and Guizhou Provinces. The South, West and North of the region are mountainous in character, mountain peaks reach 1 500m asl in the south and more than 6 000m asl in the north. In contrast the central part and the East show an undulating karst relief with average altitudes of 1 500 m

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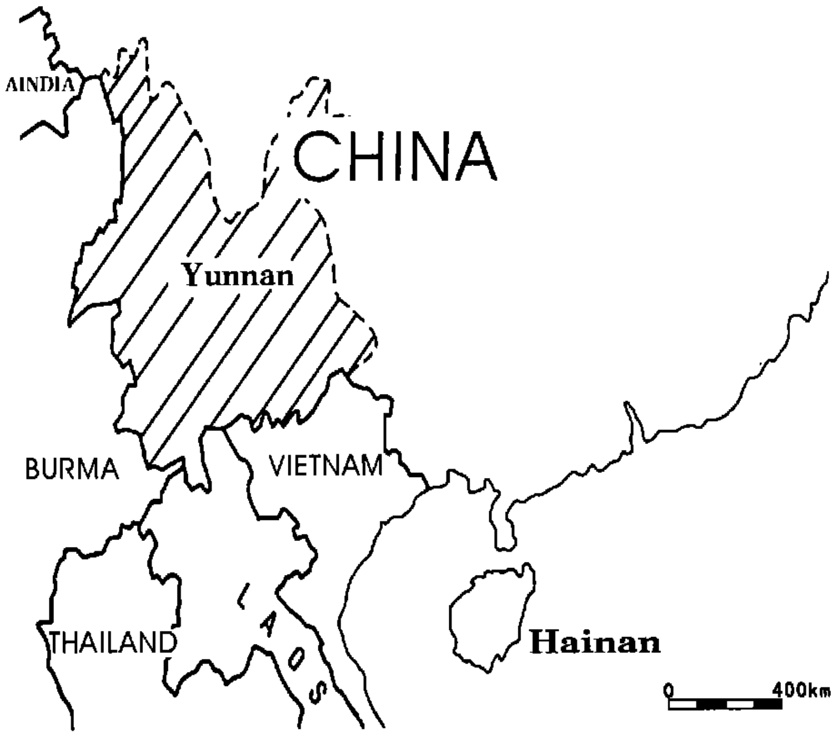

Fig. 1 The study region in Southwest China

to 2 000m asl. From a global point of view this region lies in a transition zone between the tropics and the subtropics and between 'Indian Monsoon' and 'Chinese Monsoon'. The climate is therefore monsoonal with up to 70% of the average annual rainfall occurring in the months from May to September. Through the mountains the climate is modified into numerous altitudinal climate belts. In contrast to the eastern part of the region (and south-eastern China as a whole) the dry season (or 'winter') in the western part is comparatively warm with clear skies and ample sunshine. The resulting moderate annual temperature variation has earned Yunnan Province the reputation of having 'spring all year round'.

This climatic division between East and West is due to the influence of different monsoonal airflows, namely south-westerlies in West Yunnan and south-eastern and north-eastern winds east of a meridional line along appr. 103° East. In summer Southwest and Southeast Monsoon converge along this line in East Yunnan and South Sichuan. As both airmasses originate from the tropical 'Indian Monsoon' they have the same meteorological characteristics and moist and warm conditions prevail over all of the region. With the retreat of the summer monsoon system the continental Northeast Monsoon influences the North and East of the region and nontropical westerlies dominate the Northwest. South and West remain under a south-westerly airflow of continental airmasses from India leading to dry and moderately cold conditions. At the convergence line between south-western and northeastern airmasses the so called 'Kunming quasi-stationary front' develops (Zhang 1988), named after the nearby provincial capital of Yunnan Province, resulting in overcast and rainy conditions in the East. As a net result both topography and seasonal distribution of different airmasses lead to the creation of regional climates within the region each affecting *PET* in their specific manner.

3 Estimation of Evapotranspiration

Since the publication of his paper on estimating *PET* the method of Penman (1956) has gained wide acceptance. Other methods, namely those of Haude (1952), Makkink (1957), Thornthwaite (1948) and

Turc (1954), are often used were only a limited set of climatic data is available. Although the Thornthwaite method, which utilizes only temperature records to calculate *PET*, is very popular data by Mather (1978) and own calculations showed that Thornthwaites method severely overestimates *PET* during the monsoon season. This confirms that Thornthwaites method will give wrong results when used to compare regions or seasons with equal temperatures but differing values for solar radiation and wind speed. The accuracy of the other methods depends partly upon the climate of the region under survey, as some of them have been designed for a specific region. In contrast calculating *PET* according to a Penman equation offers the best results under a variety of different climates (Doorenbos and Kassam 1986), though the need for data sets for relative humidity, solar radiation (or sunshine duration or cloudiness) and wind speed, which are measured only at meteorological observatories, limits its application. Besides the general interest by climatologists *PET* has practical applications such as the calculation of the agricultural water balance of crops. To simplify the calculation of *PET* the Food and Agriculture Organisation (FAO) has presented a modified Penman equation (Doorenbos and Pruitt, 1977, Doorenbos and Kassam, 1986) which incorporates a diurnal wind function term and allows for the change of the psychrometric constant with altitude

$$PET = c \cdot (W \cdot R_n + (1 - W) \cdot f(n) \cdot (ea - ed)) \quad (1)$$

Where c is the correction factor for the diurnal wind speed change, W is a temperature and altitude dependant weighing factor, R_n net solar radiation (in equivalent evaporation), $f(n)$ the wind run function and $(ea - ed)$ the water vapour saturation deficit. As no useful values for the diurnal wind speed change were available c was set to 1.0.

R_n is the difference between incoming short-wave radiation R_s and outgoing longwave radiation R_l. R_n was calculated from values for extra terrestrial radiation R_a, percentage of actual received radiation $R\%$ (derived from cloudiness values with the relation n/N between actual n and maximum possible sunshine hours N) and albedo (assumed to be 0.25) in the form of

$$R_n = R_a \cdot R\% \cdot (1 - \alpha) \quad (2)$$

R_l consists of the effects of temperature $f(T)$ and vapour pressure $f(ea - ed)$ on outgoing longwave radiation and cloudiness $f(n/N)$ on reflected longwave radiation

$$R_l = f(T) \cdot f(ea - ed) \cdot f(n/N) \quad (3)$$

Calculation procedures and tabulations were used as given by Doorenbos and Pruitt (1977), p. 15~28. In the Northwest of the study area only one station (Lijiang, see Fig. 2) was available in a region which constantly shows high *PET* values. In addition two nearby stations (Huaping and Yunsheng) with Class A pan evaporation measurements were used to estimate *PET*. To find appropriate values for the pan coefficient kp relating pan evaporation E_{pan} to *PET*

$$PET = E_{pan} \cdot k_p \quad (4)$$

Monthly k_p values were calculated for Lijiang and then used at the two other sites to calculate *PET*. Pan evaporation measurements are notoriously difficult to interpret (Smith 1975) and the resulting *PET* values can only serve as a first hint at the actual conditions. As an example data for 4 stations are given in Table 1.

Table 1　Mean monthly *PET* at 4 stations in Southwest China

Station	altitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jinghong	1 055 m	68.4	91.7	134.9	145.7	144.0	111.0	102.3	103.9	105.1	88.9	69.2	61.1
Kunming	1 891 m	82.2	106.7	151.2	175.2	175.7	128.3	123.7	119.3	104.6	87.5	61.7	49.1
Panxian	1 379 m	51.7	61.2	100.1	131.2	127.1	115.3	131.5	121.6	100.5	74.6	61.7	49.1
Deqen	3 585 m	57.8	56.2	79.7	92.4	108.9	104.2	100.1	93.7	82.9	76.1	62.9	58.6

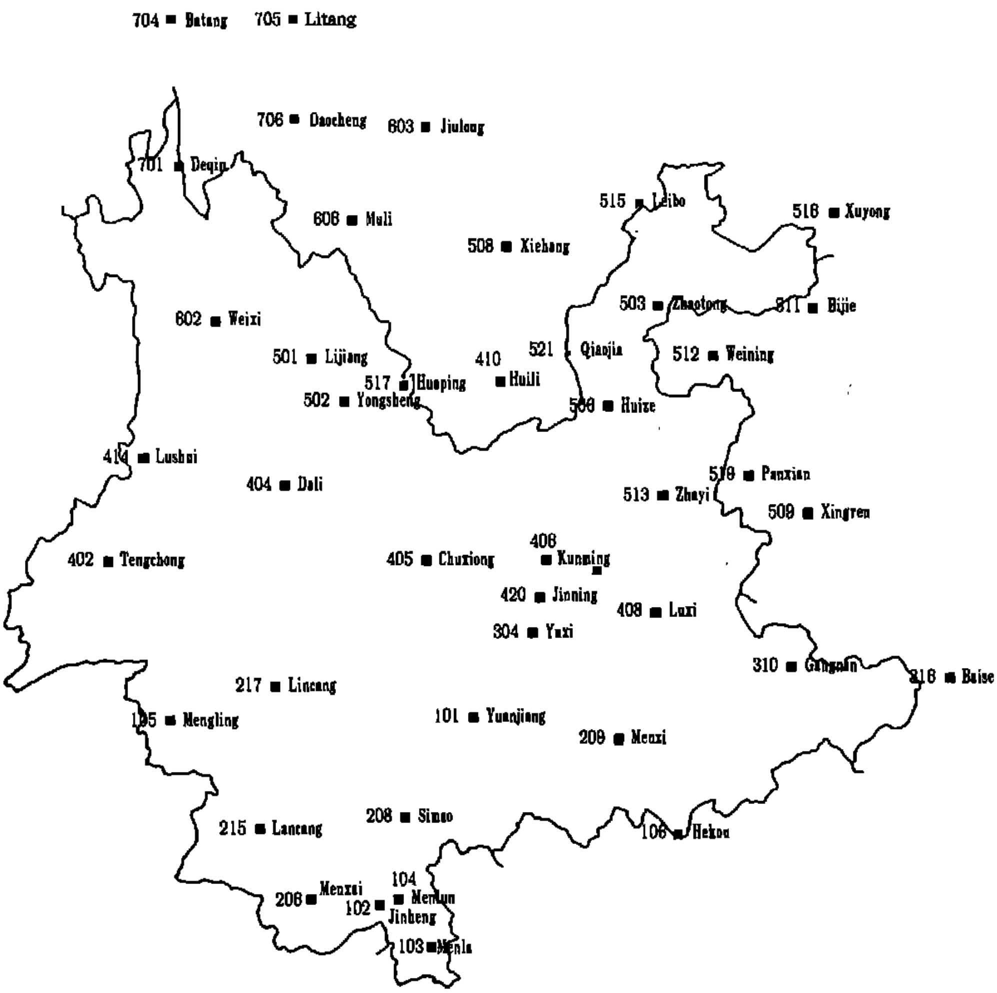

Fig. 2 Distribution of meteorological stations in the Southwest mountain region
(Numbers to the right of the symbols are station identification numbers)

4 Classification of Climate Provinces

As a final step the seasonal and spatial variation of *PET* was investigated on a monthly basis. Monthly diagrams were prepared with the altitude of the meteorological stations plotted versus mean monthly *PET*. Stations which were considered to belong to a climatically homogenous region (a 'climate province') were grouped together. A climate province is defined as an area where all station values obey a common *PET* gradient. As the distribution of climatic parameters changes during the course of the year climate provinces may form, disappear or join to form a larger climate province.

A linear regression (least squares method) was used to calculate the monthly lapse rate of each climate province. In an iterative process the allocation of stations to the climate provinces and therefore the position of the borders of the climate provinces was changed until a satisfactory result was obtained. The criterion for goodness of fit were the correlation coefficient, its significance level and relative and absolute differences of the individual station values from the regression line.

Despite the use of 36 stations two climate provinces were defined by only three stations, so that the resulting lapse rates are only preliminary. In all cases at least five stations defined a climate province, the correlation coefficients being significant at least at the 1% level.

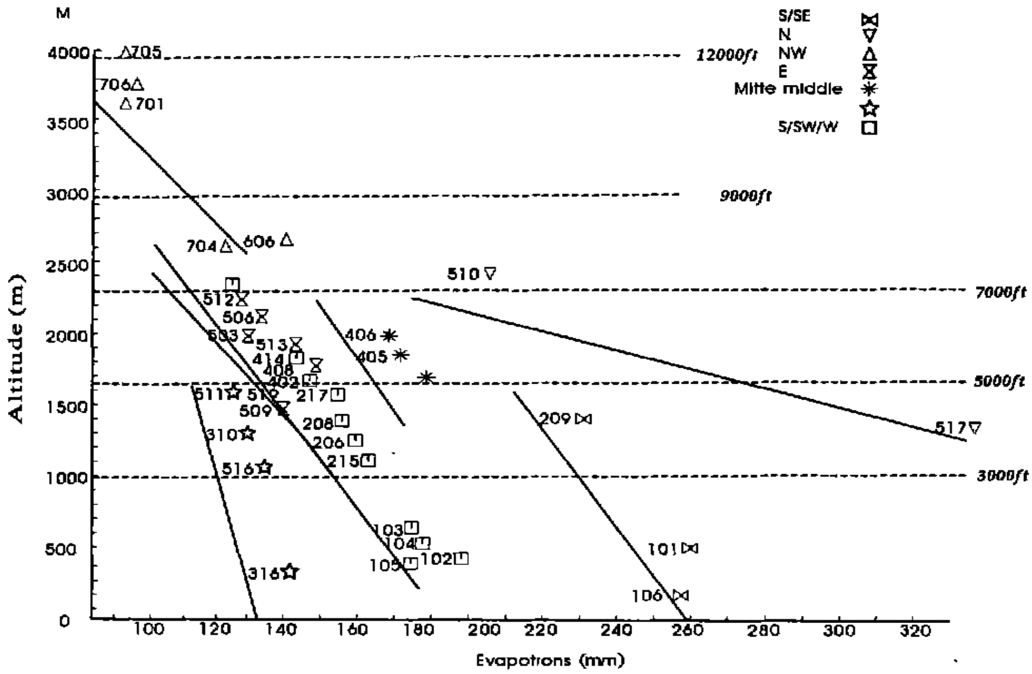

Fig. 3 Plot of estimates of *PET* versus altitude of observation for the premonsoon month of April. Symbols represent calculated station values, numbers are station identification numbers. Refer to membership in climate provinces in the following figure. Lines are representing calculated lapse rates for climate provinces

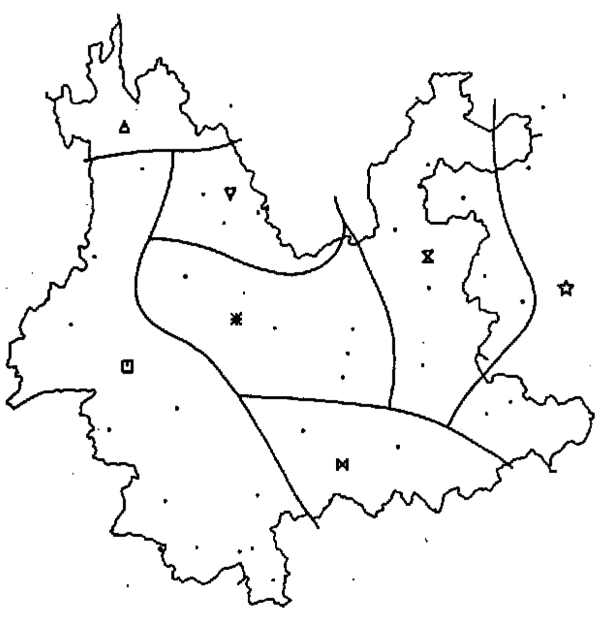

Fig. 4 Climate provinces in the premonsoon month of April (Symbols refer to station membership in Fig. 3)

5 Spatial and Seasonal Variation of *PET*

On the basis of the monthly diagrams three 'seasons' can be discerned: premonsoon, monsoon and postmonsoon. While the same method allows a rather precise distinction between seasons for precipitation or temperature, the transitions are more fluent at least in some parts of the region when *PET* is considered. On the other hand small climate provinces with distinct features emerge which can be used for a division.

5.1 Premonsoon Season

The premonsoon lasts from February to May. In a cloud free band from the Southeast to the Northwest the highest solar radiation values of the year are measured while at the same time strong winds occur in the mountains of the Northwest and Southeast. In these two areas *PET* values reach the annual maximum of 250 mm — 320 mm / month (Figs. 3 and 4). Central Yunnan still records about 160 mm / month. The East and the eastern parts of the Northeast and Southeast are cloud covered and consequently have lower *PET* rates of about 120 mm / month. In the South and West, which is usually cloud free during the premonsoon months, the onset of the monsoon can be as early as April (Thomas 1993), consequently the low April values in Fig. 3 signify that the first signs of a monsoonal cloud cover have already developed. Despite similar values and lapse rates stations in the East and South and West have to be grouped into two separate groups as these two regions are under influence of different climatic regimes. With the exception of Northeast and Southeast lapse rates show an altitudinal decrease of 2 mm / 100 m ~ 3 mm / 100 m.

5.2 Monsoon Season

June is usually considered the first month of the monsoon though it is only in July that the summer monsoon is fully developed. The whole region is under the influence of the same moist warm air mass, consequently *PET* values vary only insignificantly and individual climate provinces with high *PET* values have disappeared (Figs. 5 and 6). Fig. 5 shows that while in the East the four climate provinces of the premonsoon have merged, extent and position of the climate provinces in the West have remained basically the same.

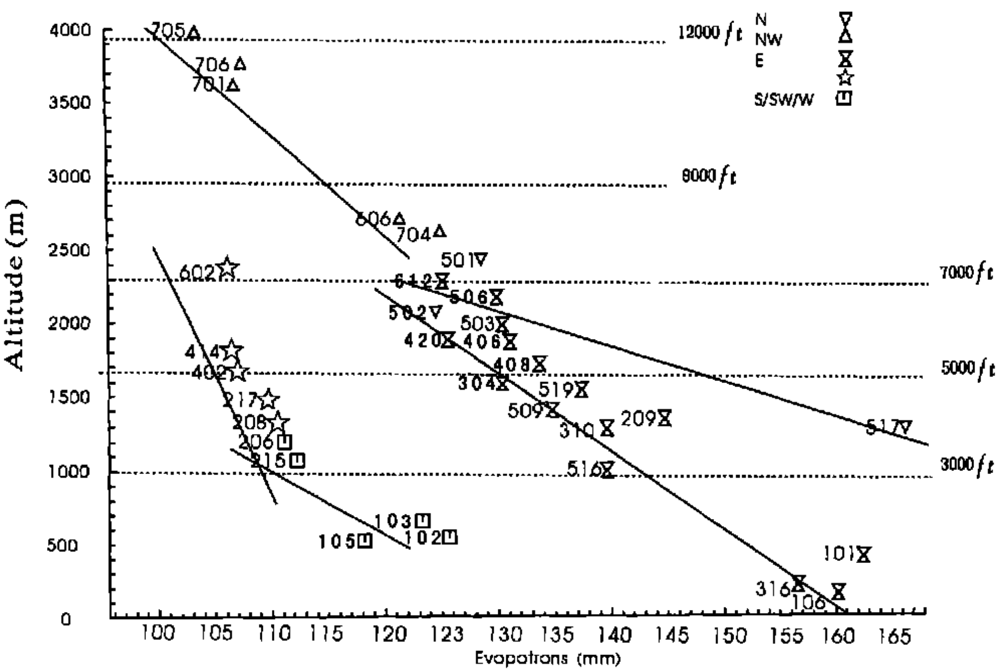

Fig. 5 Plot of estimates of *PET* versus altitude of observation for the monsoon month of July (Explanations are as in Fig. 3)

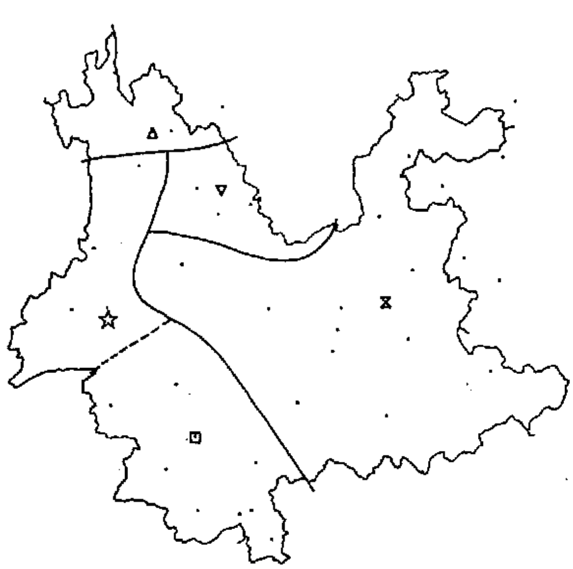

Fig. 6 Climate provinces in the monsoon month of July (Symbols refer to station membership in Fig. 5)

A closer inspection reveals that instead of the usual linear altitudinal decrease of *PET* the Southwest and West show a strong non-linear tendency which has been approximated by two linear regression lines. The point of strongest inflexion at an altitude of 1 000 m coincides with the lowest cloud deck in the South and West. Above this level the decrease is almost linear. Heavy rains and a continuos cloud cover are thought to be responsible for *PET* values of 100 mm ~ 125 mm/month. For the remainder of the region a lapse rate of −2 mm / 100m describes with good precision the *PET* distribution. *PET* values vary between 125 mm ~ 160 mm / month. Only in the Northwest do low areas show a higher *PET*, a tendency which can be observed already during the premonsoon. Stations above 2 400 m asl (which without exceptions are situated in the North and Northwest) begin to develop a tendency of having higher *PET* values than lower stations. The level of inversion suggests again that it is connected to a cloud deck, which can be deduced both from the altitudinal precipitation distribution and from a cloud forest at this altitude, which is a prominent vegetation feature in the North and Northwest. Above that level solar radiation is unimpeded by clouds, in September *PET* rates in 1 600m asl in Central Yunnan are the same as at 3 000m asl in the Northwest.

5.3 Postmonsoon Season

The postmonsoon season (October-December) shows to some degree the same distribution of climate provinces like the premonsoon (Figs. 7 and 8). The two climate provinces with high *PET* values in the Northwest and Southeast have however reappeared but the remainder of the region can be grouped into just three climate provinces. The distinction between central and eastern climate provinces which is clearly visible in premonsoon April has not yet redeveloped. The *PET* decrease is appr. －2mm/100m in the Southwest, Southeast and West and －5mm/100m in Central Yunnan and the East.

In the months from November to March stations at high altitudes may experience sub-zero temperatures. In January the frost line sinks to its lowest annual level at about 3100 m asl. While some *PET* can occur even under these condition given a sufficient amount of solar radiation no *PET* values have been calculated for three stations of the northern climate province above that line. As a surprise comes a positive lapse rate (＋1 mm / 100 m) in the Northwest which could be attributed to developments of cold air lakes and fog in low valleys and basins while higher stations enjoy clear skies and sunshine. Positive lapse rates in other postmonsoon months support the reality of this phenomenon but as *PET* values of two of the stations have been derived from pan evaporation measurements further studies are necessary to validate this result. During the postmonsoon month of December *PET* values reach their lowest level during the course of the year. In January, the coldest month of the year, *PET* values are already rising again.

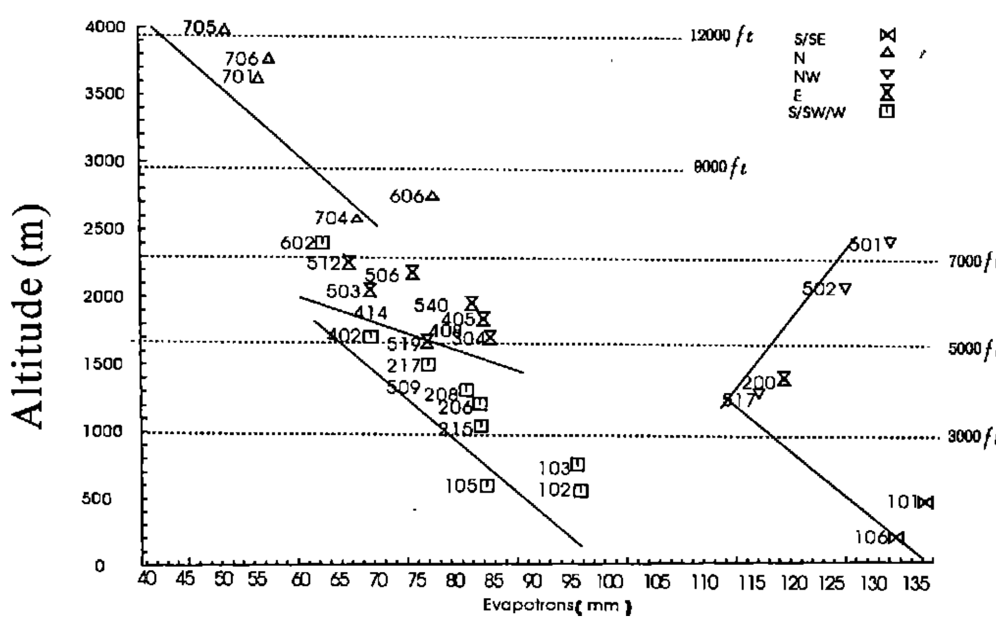

Fig. 7 Plot of estimates of *PET* versus altitude of observation for the postmonsoon month of January (Explanations are as in Fig. 3)

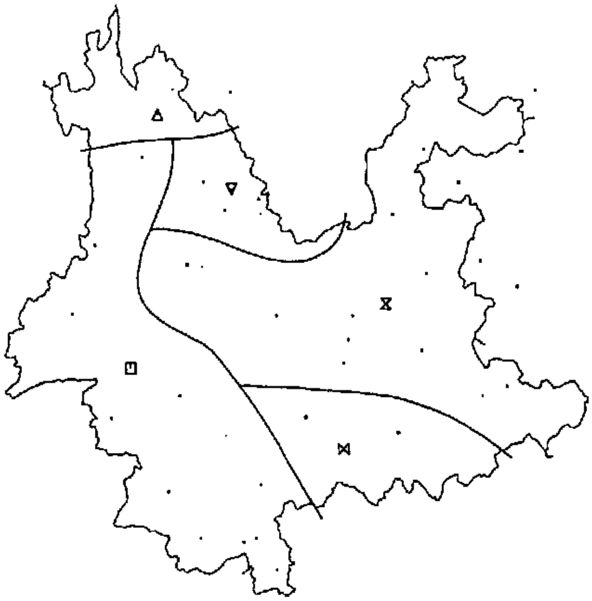

Fig. 8 Climate provinces in the postmonsoon month of January (Symbols refer to station membership in Fig. 7)

6 CONCLUSIONS

The spatial distribution of *PET* in the mountains of Southwest China supports the idea that *PET* does not necessarily decrease with altitude and that in tropical and subtropical mountains *PET* can reach rather large values at high altitudes (Henning and Henning 1982). The small-scale pattern of the seasonal distribution of airmasses is easily visible in the spatial distribution of climate provinces. In the western part of the region boundaries between climate provinces remain stable all year round indicating the steady influence of the Southwest Monsoon on the climate. The eastern half of the region experiences different seasonal air masses and therefore a changing pattern of climate provinces. *PET*, due to its nature as a 'synergetic' climate element influenced by several other climatic elements, should therefor be given more attention when considering components for climatic classifications.

During the course of the year lapse rates vary only slightly between −1mm/100mm and −5mm/100 m. As a consequence the spatial differences in a given month at a given altitude are mainly not a question of different gradients but mainly one of different intercepts of the regression lines representing the *PET* decrease. The lapse rates are only about 10% of the value found in the European Alps (Baumgartner and Reichel 1978).

Seasonal differences in *PET* are thought to be linked primarily to the interannual variation of cloudiness resp. solar radiation. Cloud decks at different altitudes can lead to a strongly non-linear decrease of *PET* or even to inversions when high altitude sites are situated above the cloud level. Temperature plays a secondary role in estimating *PET*. The intraannual extrema of *PET* are clearly not linked to those of temperature: the annual maximum and minimum of temperature is recorded in July and January, resp. while maximum and minimum of *PET* occur in April and December. Consequently the Thornthwaite equation should not be used when *PET* is to be estimated in a monsoon climate, as temperature alone does not represent the climatic environment that defines *PET*.

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中国西南山区蒸散发能力的季节和空间变化

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摘要：从全球范围来看，中国西南山区位于热带与亚热带、印度洋季风与中国季风的过渡带，属于季风气候。5～9月的降水占全年平均降水量的70%，整个山区随海拔高度的变化形成了很多气候带，与中国东部相比，中国西南山区旱季（冬季）温暖，光照充足，天空晴朗。

根据中国西南山区36个（主要是云南的）气象站观测资料，利用彭曼修正式估算了中国西南山区蒸散发能力（*PET*）。观测资料统计显示这些气象站位于同一气候区的不同类型区域，本文中估算了不同类型区域的月平均 *PET* 的递减率。

各种气候类型区域的季节变化反映了季风影响的程度，*PET* 的年内变化可划分为季风前期、季风期和季风后期。*PET* 的区域月递减率在 1mm/10mm～－5mm/100mm 间变动，较低的云雾或云层等局部气候将太阳辐射控制在低水平，影响 *PET* 的递减率的正、负变化，由太阳辐射和风速主导大部分区域 *PET* 的最大值出现在季风来临前的2～5月份。在6～9月的季风期，中国西南山区受西南季风控制，整个区域气候变化比较一致，*PET* 的值较小，其空间变化也较小。

关键词：西南山区；蒸散发能力；季风