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Estimation of annual actual evapotranspiration from nonsaturated land surfaces with conventional meteorological data

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Abstract Views diverge greatly on the relationship between actual evapotranspiration (AE) and potential evapotranspiration (PE). Penman showed that AE is determined in intensity by PE and changes proportionally as a function of PE. In contrast, Bouchet indicated that AE determines PE and varies inversely with PE. Based on nearly 30 years data from 432 weather stations and 512 hydrological stations in China, the two different theories, Penman's assumption and Bouchet's complementary relationship between AE and PE, were tested on nine river basins. With data integration technique, the complementary relationship between AE and PE was displayed entirely. A general model to estimate the actual evapotranspiration from nonsaturated surfaces by routine meteorological observations has been established on the basis of thorough analysis of the concept of PE. The results show that the calculations are all in error control of <10%, except for a few years over the Yellow River Basin.

Keywords: complementary relationship of evapotranspiration, potential evapotranspiration, actual evapotranspiration.

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Land surface evapotranspiration is an important component both in earth surface heat and water balance, on whose budgets weather and climate depend, to a great extent, for their changes are responsible for the formation and variation of vegetation features on the globe. Besides, the evapotranspiration is an important topic of short-term flood forecasting and the estimation of runoff from mountainous sides. As a result, the problem as to the evapotranspiration has been one of the concerns in the communities of geosciences and biology of the globe[1]. As we know, it is difficult to obtain a sufficient volume of reliable instrumental AE measurements, so scientists have made use of a range of theoretical, especially climatological, methods for the purpose.

Penman[2] asserted that for insufficient water supply, AE is proportional to PE, with the intensity relying on water availability. This view finds a wide range of applications in estimating AE. Numerous studies made at home and abroad have so far been based upon this hypothesis, with focus on seeking factors in relation to water availability, e.g. water contained in soil[3—7]. Yet, this is but a hypothesis and no strict theoretical support and evidence have to date been provided[8].

On the other hand, divergence of views on evapotranspiration remains among scientists.

Bouchet[8] proposed that AE equals PE over 1—10 km^2 homogeneous areas in the presence of enough water supply; as soil water is diminished, so is AE and thus the energy consumed previously on evapotranspiration becomes surplus and goes into the near-surface layer to cause changes in strength of temperature, humidity and turbulence, thereby leading to reinforced PE. With no advection present but radiation kept constant, it is supposed that AE reduction and PE augmentation should be at the same amount, which is referred to as a complementary relationship between AE and PE and put into the form

$$\mathrm{d}E_{\mathrm{Ta}} + \mathrm{d}E_{\mathrm{p}} = 0, \quad (1)$$

where E_{Ta} and E_{p} denote AE and PE, respectively.

With entirely wet and dry boundary conditions taken to integrate eq. (1), we have

$$E_{\mathrm{Ta}} + E_{\mathrm{p}} = 2E_{\mathrm{p,w}}, \quad (2)$$

in which $E_{\mathrm{p,w}}$ stands for the evapotranspiration with AE=PE for an utterly wet surface, which Bouchet called "wet-environment evapotranspiration".

As stated before, Penman assumed that PE (AE) is the cause (result), PE determining AE, a view in entire opposition to that of Bouchet. In Penman's view, besides, AE varies in direct proportion to PE, but Bouchet held that AE changes in the inverse ratio of PE.

In the context of the introduced data we address the complementary relationship between AE and PE, and develop, through intensive study of the PE concept, a general model for estimating land surface AE from the conventional meteorological data and test it against the observations of the 9 river basins to determine the calculation parameters.

1 Data sources and determination of research basins

Regional (denoting basins, the same below) mean AE was dealt with in terms of a water equilibrium scheme. Without taking into account the water interexchange with neighboring regions, the water balance of a region can be expressed as

$$E_{\mathrm{Ta}} = P - R \mp \Delta W, \quad (3)$$

where E_{Ta} = regional mean AE, P = regional mean precipitation, R = regional mean runoff and ΔW = a variable of water contained in soil over the area. $\Delta W \approx 0$ is set to be the long-range mean so that

$$E_{\mathrm{Ta}} = P - R. \quad (4)$$

Due to the fact that precipitation and runoff are measurable, formula (4) is a useful expression for calculating the long-term averaged AE over the region.

Since rainfall has its spatially uneven distribution, a network of densely-distributed stations is indispensable for the acquisition of reliable multi-yearly mean AE. Therefore, data used here were taken from 432 meteorological stations given in *Rainfall Records of China* and 512 hydrological stations in *Statistics of Hydrological Features of Major Rivers of China* to ensure the relative accuracy of estimated rainfall over the research regions (basins)1).

Selection of the basins follows the following principles: (i) to keep the long-term mean $\Delta W \approx 0$ there should be no establishment of large- and medium-size water bodies like reservoirs during the study time phase over the region; (ii) the number of meteorological and hydrological stations should be big enough; (iii) the distribution of the selected regions should be relatively scattered, with not too big a drainage area in order to indicate characteristic climates in different parts of the country. In accordance with these requirements, we singled out the 9 river basins (see table 1) by use of the *Database of Resources and Environment of China* (at a scale of 1: 4000000) and the geographic information system (GeoStar).

The adopted monthly meteorological data came from *Mean Temperatures of China*, *Humidity Datasets of China*, *Wind Data of China* and *Insolation Hours of China*. Meteorological data for some years were supplemented from the *Yearbook of Surface Meteorologi-*

1) These data were obtained from the Data Center of the Nanjing Institute of Meteorology.

cal Records of China. The monthly meteorological elements were the arithmetic means. The hydrological data, including annual mean runoff depth and yearly evaporation pan observations, were taken from *Statistics of Hydrological Features of Major Rivers in China*[1)].

Table 1 Typical runoff stations of the studied river systems

River system	Runoff station	Drainage area/km^2	Period
Minjiang River	Zhuqi	54500	1951—1979
Jialingjiang River	Beipei	156142	1952—1979
Yuanjiang River	Taoyuan	85223	1952—1979
Wujiang River	Wulong	83035	1952—1979
Yellow River[a)]	Lanzhou	222551	1951—1979
Huaihe River	Wangjiaba	30630	1955—1979
ditto	Lutaizi	91620	1951—1979
ditto	Bengbu	121330	ditto
Songhuajiang River	Fuyu	77400	1955—1979

a) The annual data of river runoff depth consist of 1951—1967 before Liujiaxia Reservoir was built and 1968—1979 after its construction for separate statistics.

2 Verification of the PE-AE relation

Despite the fact that evaporating pan measurements are atypical of the evaporation from an actual water surface, both are related rather closely[9]. The annual evaporation data taken from 80-cm-across inserted pans were employed as the index of regional PE and the difference between precipitation (*P*) and runoff depth (*R*) on a yearly basis served as the index of regional AE. The annual precipitation (*P*) denotes the index of land surface wetness used to test the PE-AE relationship (see fig. 1).

It is seen therefrom that in spite of the differences in geographic location, radiation intensity and surface wetness the complementary relationship between AE and PE differs in features from one region (basins) to another but it is noticeable. In fact, the differences arise on account of the discrepancy of surface wetness (fig. 1). In other words, had the surface wetness covered all states or levels (from extreme wetness to dryness) in the study time period for a given region, the complementary relationship between AE and PE would have included all cases.

3 Construction of a model for land surface AE

3.1 Definitions of potential evapotranspiration

Since Thornthwaite[10] proposed the PE concept in the research of climate regionalization, it has been widely utilized in meteorological, hydrological and agronomical studies. In different fields of learning, scientists developed essentially differing definitions based on their own assumptions. Granger[11] asserted that the central difficulty lies in the ambiguity of these definitions, which retarded greatly the progress in research of evapotranspiration. Therefore, it is absol-

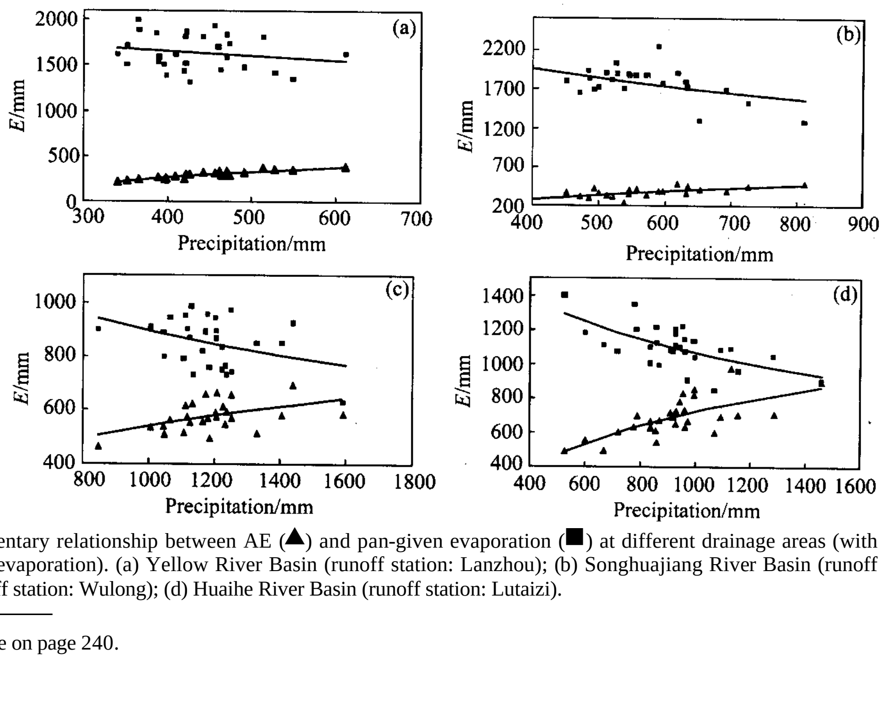

Fig. 1. The complementary relationship between AE (▲) and pan-given evaporation (■) at different drainage areas (with *E* for actual evapotranspiration or pan-given evaporation). (a) Yellow River Basin (runoff station: Lanzhou); (b) Songhuajiang River Basin (runoff station: Fuyu); (c) Wujiang River Basin (runoff station: Wulong); (d) Huaihe River Basin (runoff station: Lutaizi).

1) See the footnote on page 240.

utely necessary to make a detailed analysis of them.

Under the assumption that soil heat fluxes are neglected, the incoming net radiation energy onto an nonsaturated land surface, R_n, is transferred through turbulence into the near-surface layer by means of sensible and latent heat exchange (denoted as H and E_{Ta}, respectively), with sensible and latent heat flux values depending on turbulent exchange coefficient and the gradient between T_s (evaporating surface temperature) and T_a (near-surface layer air temperature) and that between e_s (evaporating-surface vapor pressure) and e_a (near-surface layer vapor pressure). Therefore, in exactly defining nonsaturated land surface PE, it is necessary to know clearly the changes of all the physical variables when such a surface is getting enough water supply to become saturated. Based on the assumptions of their changes and combinations, scientists have developed a range of PE definitions different in essence, as shown in the following[11].

(ⅰ) Generalized potential evapotranspiration (GPE). Under the assumption that an nonsaturated land surface obtain sufficient water supply to become saturated, the variables (R_n, H, E_{Ta}, T_s, e_s, T_a, e_a) over an evaporating surface and in the near-surface layer will experience change, attaining a new equilibrium, with $E_{p,0}$ denoting the evapotranspiration therein that means the water amount going out of a saturated land or a free water surface per unit area and time[12]. Evidently, it is impossible to find the values of these variables under the new equilibrium. Following the definition, thus, it is unlikely to give a "PE definition" in the form of an expression for estimation under the assumption that only the underlying surface is set to be merely a saturated land surface or a free water surface.

(ⅱ) Advection-free potential evapotranspiration (AFPE). By setting net radiation energy R_n of an nonsaturated land surface to be constant, T_s, T_a and e_a (see above for the meanings) will change to reach a new equilibrium by providing sufficient water supply for the surface, and the PE under the resulting balance is represented by $E_{p,pt}$. Obviously, it is impossible to calculate the foregoing variables in terms of initial conditions for the new equilibrium. Priestley and Taylor[13] developed an empirical relationship between $E_{p,pt}$ and R_n under an advection-free assumption and referred to it as the advection-free potential evapotranspiration (refer to table 2).

(ⅲ) Penman potential evapotranspiration (PPE). With an nonsaturated land surface assumed to be saturated from water supply and with R_n, T_a and e_a kept unchanged, T_s will undergo change and reach a new equilibrium. Under this assumption Penman established simultaneous equations of energy balance and vapor transmission used to seek the evapotranspiration rate under the new equilibrium, which is the Penman PE denoted by $E_{p,p}$ (see table 2).

(ⅳ) Van Bavel potential evapotranspiration (VBPE). In the process of making an nonsaturated land surface a saturated surface, T_a, e_a and T_s are let to be constant, and PE in the new equilibrium is denoted by $E_{p,v}$. With T_s known, the PE in this sense is given by Dolton equation for calculation (see table 2) and called the Van Bavel Potential Evapotranspiration[14].

(ⅴ) Equilibrium evapotranspiration (EE). In making an nonsaturated land surface a saturated surface R_n is assumed to be constant and the near-surface layer to become water-saturated. In that case the evapotranspiration rate is acquired in the new equilibrium by simplifying the Penman PE expression. The equation for equilibrium rate is defined as the equilibrium evapotranspiration expressed as $E_{p,q}$ by Slatyer and McIlroy[15].

From the above assumptions and with different combinations of the variables it is likely to give other PE definitions. Table 2 summarizes the aforementioned PE definitions with their sources.

3.2 Calculation of potential and wet environment evapotranspirations

Two PE concepts are used in the complementary relationship evapotranspiration model (see eq. (2)). To avoid confusion Bouchet[8] called them, separately, the potential evapotranspiration E_p and Wet Environment

Table 2 Summary of definitions of PE and their sources[a)]

Name	Symbol	Definition	Expression	Source
GPE	$E_{p,0}$	evapotranspiration which would occur if the surface was brought to saturation	indeterminate	[12]
AFPE	$E_{p,pt}$	evapotranspiration which would occur if the surface was brought to saturation and R_n was held constant	$E_{p,pt}=a\frac{D}{D+g}(R_n-G)$	[13]
PPE	$E_{p,p}$	evapotranspiration which would occur if the surface was brought to saturation and R_n, T_a and e_a were held constant	$E_{p,p}=\frac{D}{D+g}(R_n-G)+\frac{g}{D+g}E_a$	[2]
VBPE	$E_{p,v}$	evapotranspiration which would occur if the surface was brought to saturation and T_a, e_a and T_s were held constant	$E_{p,v}=f(\boldsymbol{u_z})(e_s^*-e_a)$	[14]
EE	$E_{p,q}$	evapotranspiration which would occur if the surface was brought to saturation and R_n was held constant and $e_a=e_a^*$	$E_{p,q}=\frac{D}{D+g}(R_n-G)$	[15]

a) Part of the content is derived from ref. [11]. Symbols in these expressions have the meanings as follows: a, a constant and is believed to be equal to 1.26 by Priestly and Taylor, but studies show that its values are in a certain range[16–18]; D, the slope of saturation vapor pressure-temperature curve at T_a equal to T_s; g, a constant of the psychrometer equation; R_n, the net radiation energy of an nonsaturated land surface; G, the soil heat flux; $E_a=f(\boldsymbol{u_z})(e_a^*-e_a)$, the dry power as an integrative parameter for the effect on evapotranspiration of such atmospheric variables in the near-surface layer as air temperature, humidity and wind; u_z, the wind at a reference height; e_a^*, the saturation vapor pressure at near-surface-layer air temperature T_a; e_a, the actual vapor pressure in the boundary-layer atmosphere; $f(\boldsymbol{u_z})$, the function of wind; e_s^*, the saturation vapor pressure at evaporating surface temperature T_s.

Evapotranspiration $E_{p,w}$. It is crucial to make a choice between them in order to construct a complementary relationship evapotranspiration model.

For PE definitions presented in the last subsection, the relations to AE in terms of estimations are as follows[19,20]:

$$E_{p,v}\geq E_{p,p}\geq E_{p,pt}\geq E_{p,q}\geq E_{Ta}. \quad (5)$$

Since T_s is hard to be determined, $E_{p,v}$ has found no widespread applications. The expressions of table 2 applicable to estimation are $E_{p,p}$, $E_{p,pt}$ and $E_{p,q}$ only. Observations show that even in the case of seas it is unlikely to make the air over the evaporating surface approaching saturation[15]. Consequently, $E_{p,q}$ represents the bottom limit of PE over a saturated land surface, but the expression of wet environment evapotranspiration $E_{p,w}$ in terms of $E_{p,q}$ gives underestimations. Hence, Morton[21], Davies and Allen[22], Brutsaert and Stricker[23] took $E_{p,p}$ as the expression for computing E_p component of their complementary relationship evapotranspiration models and used the advection-free $E_{p,pt}$ expression to calculate $E_{p,w}$ component of their model. Thus, the complementary relationship evapotranspiration model is as

$$E_{Ta}+E_{p,p}=2E_{p,pt}, \quad (6)$$

which is employed in our work, with the estimating schemes of dry power E_a, net radiation R_n and other utilized parameters determined by referring to ref. [24]. In the calculation with eq. (6) soil heat flux $G\approx 0$ is assumed on an interannual scale.

3.3 The complementary relationship model for evapotranspiration simulation

As stated in Section 2, to show a complete picture of the complementary relationship between PE and AE means to investigate a full range of land surfaces from extremely dry to surprisingly wet, which is undoubtedly impossible in practice, leading to the incompleteness of the relations. For this reason, an integration scheme is adopted to deal with the data from all the aforementioned basins (drainage areas).

The $E_{p,pt}$ expression of table 2 is put into eq. (6), leading, after rearrangement, to

$$\frac{E_{p,p}}{\frac{D}{D+g}(R_n-G)}+\frac{E_{Ta}}{\frac{D}{D+g}(R_n-G)}=2a. \quad (7)$$

The whole-region (basins) annual wetness is denoted by the ratio of yearly precipitation P to $\frac{D}{D+g}(R_n-G)$, the yearly relative PE index denoted by the ratio of $E_{p,p}$ to $\frac{D}{D+g}(R_n-G)$ and the yearly relative AE index by the ratio of E_{Ta} to $\frac{D}{D+g}(R_n-G)$ for the basins of a particular river. With the aid of the integration technique, data of all the 9 basins are put onto a diagraph to produce a full picture of the complementary relationship between PE and AE, of which E_{Ta} (i.e. AE) is obtained by the water balance equation with precipitation minus runoff, i.e. $P-R$ (see fig. 2).

Fig. 2 displays a full range of the complementary relationship between PE and AE. In fig. 2(a) the relative AE values are quite discrete, especially over the wet basins, which is dominantly related to the fact that on an interannual scale the variable for water storage $\Delta W \neq 0$ such that the difference (P–R) used to calculate E_{Ta} yields rather great errors. On an interannual scale, nevertheless, the complementary relationship between PE and AE are not dubious. But the discreteness of relative AE has been greatly reduced after the data were treated in terms of a ten-year running averaging scheme (fig. 2(b)).

3.4 Construction of the model for AE

One of the controversial points of the study on complementary relationship between PE and AE lies in the question whether AE and PE are just complementary to each other, viz., whether $dE_{Ta} = -dE_p$ holds. Granger[19,20] asserted that the ratio of the change of AE to that of PE depends on their expressions selected for use. Fig. 3 depicts the correlations between relative PE and relative AE calculations from equations $\frac{E_{p,p}}{\frac{D}{D+g}(R_n-G)}$ and $\frac{E_{Ta}}{\frac{D}{D+g}(R_n-G)}$, respectively, for which the data length n = 165.

It is seen therefrom that the relative PE and relative AE exhibit big negative correlations but are not entirely complementary. For this reason, by putting $dE_{Ta} = -b\,dE_{p,p}$, we rewrite eq. (6) as

$$b\,E_{p,p} + E_{Ta} = (1+b)\,E_{p,pt}, \quad (8)$$

into which are substituted the expressions of $E_{p,p}$ and $E_{p,pt}$ (refer to table 2), leading, after rearrangement, to a general formulation for AE that takes the form

$$E_{Ta} = A\frac{D}{D+g}(R_n-G) - B\frac{g}{D+g}E_a, \quad (9)$$

where $A = a + (a-1)b$ and $B = b$ stand for the coefficients.

3.5 Calculation result of annual AE

Eq. (9) is employed to get AE magnitudes which are treated by a ten-year running averaging scheme, leading to the AE model on an annual basis of the form

$$E_{Ta} = 1.251\frac{D}{D+g}(R_n-G) - 1.522\frac{g}{D+g}E_a, \quad (10)$$

which is equivalent to the expression for wet land surface PE developed by Priestly and Taylor for the case $a = 1.10$ The eq. (10)-calculated AE values are presented in fig. 4.

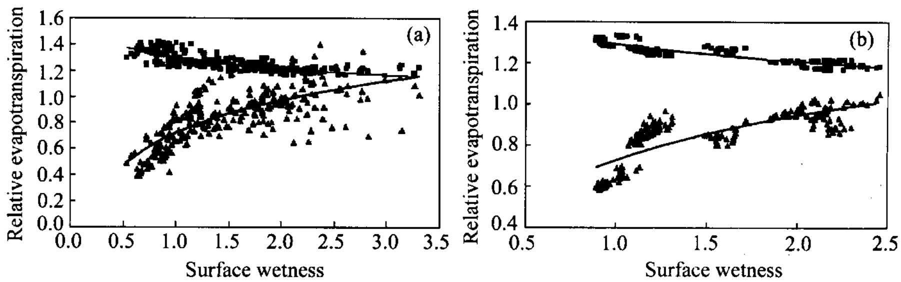

Fig. 2. Data integration chart of relative AE (▲) and relative PE (■). (a) Annual values; (b) ten-year running means.

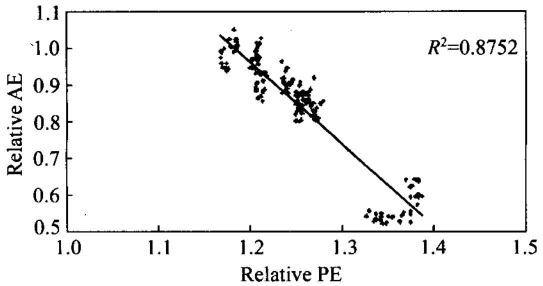

Fig. 3. Correlations between relative AE and relative PE.

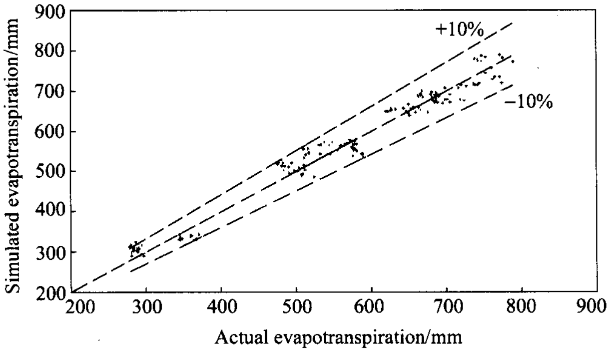

Fig. 4. Simulations of actual evapotranspiration.

It is seen therefrom that except for lower AE values in some years over the Yellow River Basins that have >10% errors (which is associated with the larger drainage area that covers quite a big part of the Qinghai-Tibetan Plateau, extensive NW China and complicated geographic factors), the others indicate <10% errors of the simulations vs. the observations. It would thus be possible to improve the accuracy of calculations to a great extent if advanced technologies like remote sensing could be adopted to acquire more exact surface parameters.

4 Concluding remarks

In the context of hydrological and meteorological data from the 9 river basins for nearly 30 years and through the data integration technique, study of evapotranspiration is undertaken, indicating that the complementary relationship between PE and AE is really available on a basin-wide scale. Taken $E_{p,p}$ as E_p and $E_{p,pt}$ as $E_{p,w}$, respectively, a general model is developed for AE over the project basins. Except for the Yellow River Basins, the errors of calculated AE vs. measured AE on a yearly basis after calculations subjected to ten-year running averaging are <10%. Based on this study we come to the following conclusions:

(1) Noticeable complementary relationship between PE and AE are available on the basin-wide scale.

(2) The theory of complementary relationship between PE and AE takes into account the feedback of regional evapotranspiration upon the near-surface layer atmosphere, thus making clear the cause-effect between AE and PE. But the mechanism awaits further research.

(3) The data integration method adopted is capable of giving a full picture of the complementary relationship between PE and AE, thus providing greater likelihood for model establishment.

(4) Given a particular PE definition (see table 2), the choice of effective expressions for potential evapotranspiration and wet environment evapotranspiration conduces to the construction of a general model for AE.

(5) The complementary relationship between PE and AE discussed here needs to be verified and advanced by means of still more data of this kind.

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