

The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration

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[1] Potential evapotranspiration (PET) is one of the inputs to the Palmer Drought Severity Index (PDSI). A common approach to calculating PDSI is to use the Thornthwaite method for estimating PET because of its readily available input data: monthly mean temperatures. PET estimates based on Penman-type approaches are considered to be more physically realistic, but require more diverse input data. This study assesses the differences in global PDSI maps using the two estimates for PET. Annually accumulated PET estimates based on alternative Thornthwaite and Penman-Monteith, parameterizations have very different amplitudes. However, we show that PDSI values based on the two PET estimates are very similar, in terms of correlation, regional averages, trends, and in terms of identifying extremely dry or wet months. The reason for this insensitivity to the method of calculating PET relates to the calculations in the simple water balance model which is at the heart of the PDSI algorithm. It is shown that in many areas, actual evapotranspiration is limited by the availability of soil moisture and is at markedly lower levels compared to its potential value. In other areas, the water balance does change, but the quantity central to the calculation of the PDSI is, by construction, a reflection of the actual precipitation, which makes it largely insensitive to the use of the Thornthwaite PET rather than the Penman-Monteith PET. A secondary reason is that the impact of PET as input to a scaling parameter in the PDSI algorithm is very modest compared to the more dominant influence of the precipitation.

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1. Introduction

[2] Monitoring changes in the occurrence of droughts and length of dry spells is of obvious importance since droughts, and floods, are directly relevant for food and water supply. The need for drought monitoring is stressed by the observation that many simulations of possible future climates predict summer desiccation in the midlatitudes of the Northern Hemisphere [Meehl *et al.*, 2007].

[3] Data on precipitation alone are not necessarily good indicators of drought. A drought, from the perspective of agriculture, is one which is determined by conditions which lead to stunted growth or even wilting of crop plants. These involve persistently high levels of potential evapotranspiration (PET), where the crop is unable to maintain itself by extracting water from the soils, combined with low levels of soil moisture content. Long-term changes in global soil moisture levels are difficult to monitor since this quantity is

measured at relatively few stations that are unevenly spread across the globe [Robock *et al.*, 2000]. Proxy measures, like the Palmer Drought Severity Index (PDSI), are therefore commonly used [Guttman, 1991]. The PDSI is a measure of regional moisture availability that has been used extensively to study droughts and wet spells but also to place recent and historical events in the context of the long record of drought history [Palmer, 1965; Dai *et al.*, 1998; Heim, 2002; van der Schrier *et al.*, 2006a, 2006b, 2007; Dai *et al.*, 2004; Dai, 2011].

[4] The computation of the index involves a classification of relative moisture conditions within 11 categories as defined by Palmer [1965] (Table 1). The index is based on water supply and demand which is calculated using a rather complex water budget system based on records of precipitation and temperature, with the soil characteristics of the site taken into consideration. Traditionally, the parameterization used for calculating potential evapotranspiration was the one proposed by Thornthwaite [1948]. This required only readily available input data for estimating land-surface evapotranspiration, explaining its popularity. This parameterization is based only on daily averaged temperatures and latitude, the latter variable used to calculate the maximum amount of sunshine duration.

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Table 1. Classification of Dry and Wet Conditions as Defined by Palmer [1965] for the Palmer Drought Severity Index (PDSI)

PDSI	Class
≥ 4.0	extremely wet
3.0: 4.0	severely wet
2.0: 3.0	moderately wet
1.0: 2.0	slightly wet
0.5: 1.0	incipient wet spell
-0.5: 0.5	near normal
-0.5: -1.0	incipient dry spell
-1.0: -2.0	slightly dry
-2.0: -3.0	moderately dry
-3.0: -4.0	severely dry
≤ -4.0	extremely dry

[5] Although temporal variations in the PDSI are largely controlled by variations in precipitation rather than potential evapotranspiration [Guttman, 1991], the suggestion has been made that PDSI values computed using PET estimates from more physically based parameterizations of PET, like the Penman type approaches, are more reliable [Trenberth *et al.*, 2007, p. 261]. The latter type of parameterizations require additional input fields like wind speed, solar radiation, cloudiness and water vapor content. The most obvious candidate for the calculation of PET would be the FAO-endorsed Penman-Monteith parameterization [Allen *et al.*, 1994a, 1994b] which calculates reference crop evapotranspiration and is a measure for potential evapotranspiration.

[6] The aim of this study is to investigate the dependence of the PDSI on the alternative Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. Estimates by both potential evapotranspiration formulae are calculated and combined with one precipitation data set in order to produce two PDSI data sets. The drought metric used in this study is the self-calibrating PDSI [Wells *et al.*, 2004], a variant of the PDSI, which is more appropriate for geographical comparison of climates of diverse regions [van der Schrier *et al.*, 2006a].

[7] A comparison between the Thornthwaite and the Penman approach, as well as three other radiation-based parameterizations, has recently been conducted by Donohue *et al.* [2010] for Australia, but there are many other studies on this topic [e.g., Hobbins *et al.*, 2008; Douglas *et al.*, 2009; Weiss and Menzel, 2008]. Dai [2011] touched on the influence of the PET parameterization on PDSI values when he evaluated the linear trends in PDSI data sets forced by similar precipitation amounts but different estimates of the PET. In the present study, the comparison will include more aspects of the PDSI and will focus on the explanation of the observed relation between PDSI and PET.

2. Methods

2.1. Self-Calibrating PDSI

[8] In the years since its development, the PDSI has become a standard for measuring meteorological drought. However, the PDSI has been criticized for a variety of reasons of which the most significant is perhaps that it is not comparable between diverse climatological regions, despite Palmer's efforts to ensure that it would be. This is a particular drawback when a global gridded PDSI climatology is produced.

[9] The self-calibrating PDSI (scPDSI) as devised by Wells *et al.* [2004] is a more appropriate metric for a global data set. Where Palmer used weighting and calibration factors in his algorithm, empirically derived from a limited amount of data from the U.S. Great Plains, the self-calibrating PDSI determines these factors for each location separately. This calibrates the PDSI with a set of factors uniquely appropriate to that location, and affects the range of values of the self-calibrating PDSI and its sensitivity for changes in the moisture regime [Wells *et al.*, 2004; van der Schrier *et al.*, 2006a].

[10] The calibration interval used here is 1951–2006. The exclusion of the 1901–1950 period from the calibration period is justified by the relative scarcity of station data outside North America and Europe in this period.

[11] Palmer specifically designed the index to treat the drought problem in semiarid and dry subhumid climates and cautioned that extrapolation beyond these conditions may lead to unrealistic results [Palmer, 1965, p. 50]. He also stated that some regions are so near to being a desert that there is really little point in attempting drought analysis in such situations. This conclusion is equally relevant for the self-calibrating PDSI and it is for this reason that we do not calculate PDSI values in situations where the accumulated precipitation over the 1951–2006 calibration period is less than 5000 mm, which mainly affects the Sahara region, parts of the Arabian Peninsula, part of northern China and parts of Chile.

[12] From the perspective of this study, it is relevant to point out how potential and actual evapotranspiration affect the drought index. The hydrologic accounting procedure of the water balance model involves the production of time series of the runoff values, recharge to the soils, moisture loss from the soils and transpiration, as well as estimates of their potential values. From these time series, average monthly values of the potential and the actual values are calculated over the calibration interval. The coefficient of evapotranspiration α for a particular month is the quotient of an average of the actual value \overline{ET} and the average of the potential value \overline{PET} for that month. Similar coefficients are β , giving the ratio of average recharge to the soils \overline{R} and its potential value \overline{PR} , γ , giving the ratio of average runoff \overline{RO} and its potential value \overline{PRO} , and δ , giving the ratio of average loss of moisture from the soils \overline{L} to its potential value \overline{PL} . Here the overbar denotes a long-term average. Palmer's 'Climatically Appropriate For Existing Conditions' (CAFEC) precipitation \hat{P} is a function of the potential evapotranspiration, potential recharge, potential runoff and potential loss, weighted by their appropriate coefficients,

$$\hat{P} = \alpha PET + \beta PR + \gamma PRO - \delta PL. \quad (1)$$

Equation (1) is analogous to a simple water balance where precipitation is equal to evapotranspiration plus runoff, plus or minus any change in soil moisture storage [Alley, 1984]. It is the difference between the actual precipitation P and the CAFEC precipitation \hat{P} that is, downstream from this point in the parameterization, the central quantity on which the PDSI is based. Palmer coined the term "moisture departure" d for this difference,

$$d = P - \hat{P}. \quad (2)$$

Note that the quantities used in the PDSI algorithm are monthly dependent, but here this is not made explicit in the formulae for notational convenience.

Table 2. Parameters and Their Descriptions for All Components of Equation (8)^a

Parameter	Description	Unit
PET	grass reference evapotranspiration	mm d ⁻¹
R_n	net radiation at crop surface	MJ m ⁻² d ⁻¹
G	soil heat flux	MJ m ⁻² d ⁻¹
T	average temperature at 2 m height	°C
U_2	wind speed at 2 m height	m s ⁻¹
$e_a - e_d$	vapor pressure deficit for measurement at 2 m height	kPa
Δ	slope of the vapor pressure curve	kPa °C ⁻¹
γ	psychrometric constant	kPa °C ⁻¹
900	coefficient for the reference crop	kJ ⁻¹ kg K d ⁻¹
0.34	wind coefficient for the reference crop	s m ⁻¹

^aThe descriptions are from *Allen et al.* [1994b, p. 88].

[13] The other occasion where the averaged potential evapotranspiration \overline{PET} enters the PDSI algorithm is in the calculation of the climatic characteristic K' ,

$$K' = 1.5^{10} \log \left[\frac{\overline{PET} + \overline{R} + \overline{RO}}{\overline{P} + \overline{L}} + 2.8 \right] + 0.5, \quad (3)$$

where \overline{R} , \overline{RO} , \overline{P} and \overline{L} are averages of the recharge to the soils, runoff, precipitation and loss respectively. The fraction in the numerator of the argument of the logarithmic function is interpreted as the averaged ‘moisture supply’ vs. ‘moisture demand.’ The quantity \overline{D} is an average of the moisture departure over the calibration interval. Palmer noticed that using the climatic characteristic K' tended to make droughts in Tennessee more extreme than those in Kansas or North Dakota, which led him to introduce a further refinement of this coefficient, K . Here the algorithm

of the self-calibrating PDSI diverges from Palmer’s original algorithm, where the climatic characteristic K is Palmer’s K' weighted by a factor to ensure that the percentage of months classified as “extreme” ($PDSI \leq -4$ or $PDSI \geq 4$) over the calibration interval is 2% [*Wells et al.*, 2004].

2.2. Data Sets

[14] Values of potential soil moisture storage capacity are taken from the data set that make up the digital soil map of the world [*Food and Agriculture Organization*, 2003]. The water holding capacity in a grid box is taken to be the one for the most dominant soil type in that grid box. The water holding capacity of the soils is subdivided into nine classes, from wetlands (which are given a water holding capacity of 1000 mm) to soils with a water holding capacity of <20 mm. Grid boxes dominated by surface water, glaciers or icecaps are marked as absent and no scPDSI values are computed for these grid boxes. The data are regridded from 5' resolution to $0.5^\circ \times 0.5^\circ$ resolution by simple interpolation so that the grid of the water holding capacity of the soils coincides with the grids of the temperature and precipitation data.

[15] Gridded precipitation, temperature, cloud cover and vapor pressure data ($0.5^\circ \times 0.5^\circ$ resolution) are taken from the monthly set compiled by the Climatic Research Unit (I. Harris et al., Updated high-resolution grids of monthly climatic observations—The CRU TS 3.0 dataset, manuscript in preparation, 2011). This data set, designated CRU TS 3.0, currently spans the period January 1901 to December 2006. These data sets are supplemented with a gridded data set ($0.5^\circ \times 0.5^\circ$ resolution) with climatological values (1961–1990) of monthly averages of the 10 m wind speed which was also produced at the Climatic Research Unit.

[16] Station data used in the construction of the gridded data have been quality controlled and checked for inhomogeneities and adjusted where necessary [*Mitchell and*

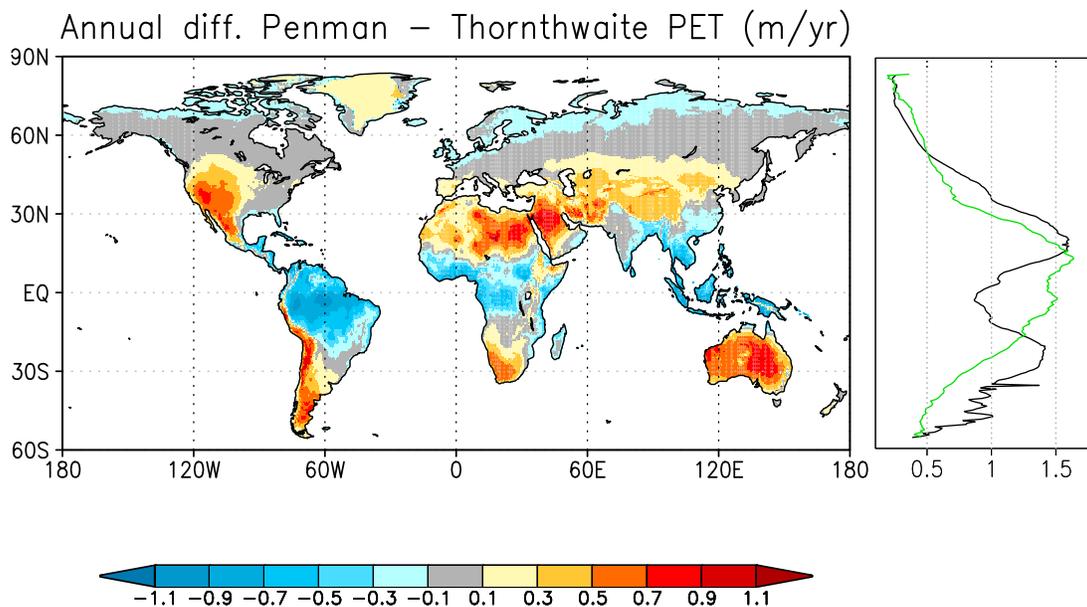


Figure 1. (left) Differences between the mean values in annually accumulated potential evapotranspiration (PET) calculated using the Penman-Monteith formula minus PET values based on the the Thornthwaite formula. (right) Zonally averaged values of the Penman-Monteith PET (black line) and Thornthwaite PET (green line). Values calculated over the 1901–2006 period.

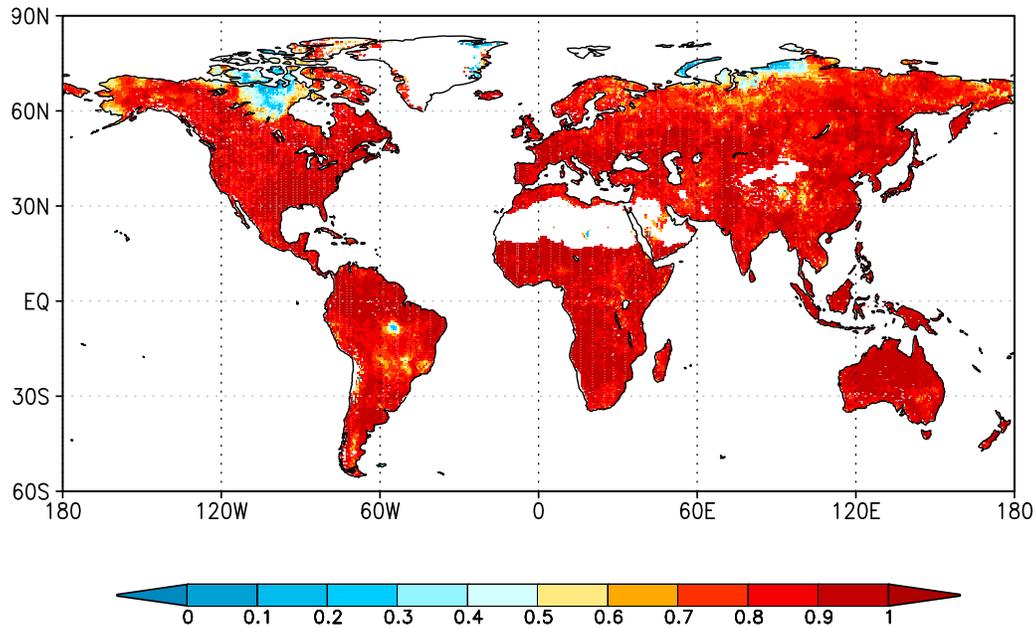


Figure 2. Point-by-point correlation of alternative yearly averaged Palmer Drought Severity Index (PDSI) values calculated using the Thornthwaite or Penman-Monteith PET estimates. The correlation are calculated over the 1901–2006 period. White areas in image show regions where the PDSI cannot be calculated, either because there is too little overall rainfall or because the water holding capacity is undefined, such as over surface waters, glaciers, or ice caps.

Jones, 2005]. Precipitation and temperature were interpolated directly from station observations. Cloud cover and vapor pressure were interpolated from merged data sets comprising station observations and, in regions or times where there were no station data, synthetic data estimated using predictive relationships with the primary variables: temperature, precipitation and diurnal temperature range [New *et al.*, 2000]. For the CRU TS data sets, anomalies with respect to the 1961–1990 normal are gridded [Mitchell and Jones, 2005] which preserves the variance better than interpolation of absolute values [New *et al.*, 2000]. The consequence of this is that in areas or times with fewer station data, the estimate of the absolute value will be close to climatology. For temperature, the station density is high enough for this effect to be small (Harris *et al.*, manuscript in preparation, 2011). The use of predictive relationships means that for cloud cover and vapor pressure, gridded values will not be exactly equal to climatological values for the periods or areas where station data for these elements are absent.

2.3. Estimation of Potential Evapotranspiration

2.3.1. Thornthwaite

[17] The relationship between monthly means of daily averaged temperatures, T , and potential evapotranspiration, PET , is given by Thornthwaite's [1948] equation 10,

$$PET = 16 \left(\frac{10T}{I} \right)^a, \quad (4)$$

where PET is in mm month^{-1} and a is given by a third-order polynomial in the heat index I [Thornthwaite, 1948, equation 9]. The heat index is developed for this purpose and has

for each year 12 monthly means of daily averaged temperature values as input [Thornthwaite, 1948, p. 89].

$$I = \sum_{i=1}^{12} \left(\frac{T}{5} \right)^{1.514}. \quad (5)$$

The numerical implementation of equation (5) is that $\max(T, 0)$ is taken as input to the summation rather than T .

[18] The implementation of Thornthwaite's original approach is slightly modified [Willmott *et al.*, 1985] where Thornthwaite's parameterization is used for a limited range of T values,

$$PET = \begin{cases} 0 & T < 0^\circ\text{C} \\ 16(10T/I)^a & 0^\circ\text{C} \leq T < 26.5^\circ\text{C} \\ -415.85 + 32.24T - 0.43T^2 & T \geq 26.5^\circ\text{C}. \end{cases} \quad (6)$$

[19] Finally, to account for variable day and month lengths, PET is adjusted to

$$PET = PET(\theta/30)(h/12), \quad (7)$$

where θ is the length of the month (in days) and h is taken as the duration of daylight (in hours) on the fifteenth day of the month [Willmott *et al.*, 1985]. The latter correction ensures that the Thornthwaite parameterization for PET is related to the latitude of the site considered, next to the monthly means of daily averaged temperatures.

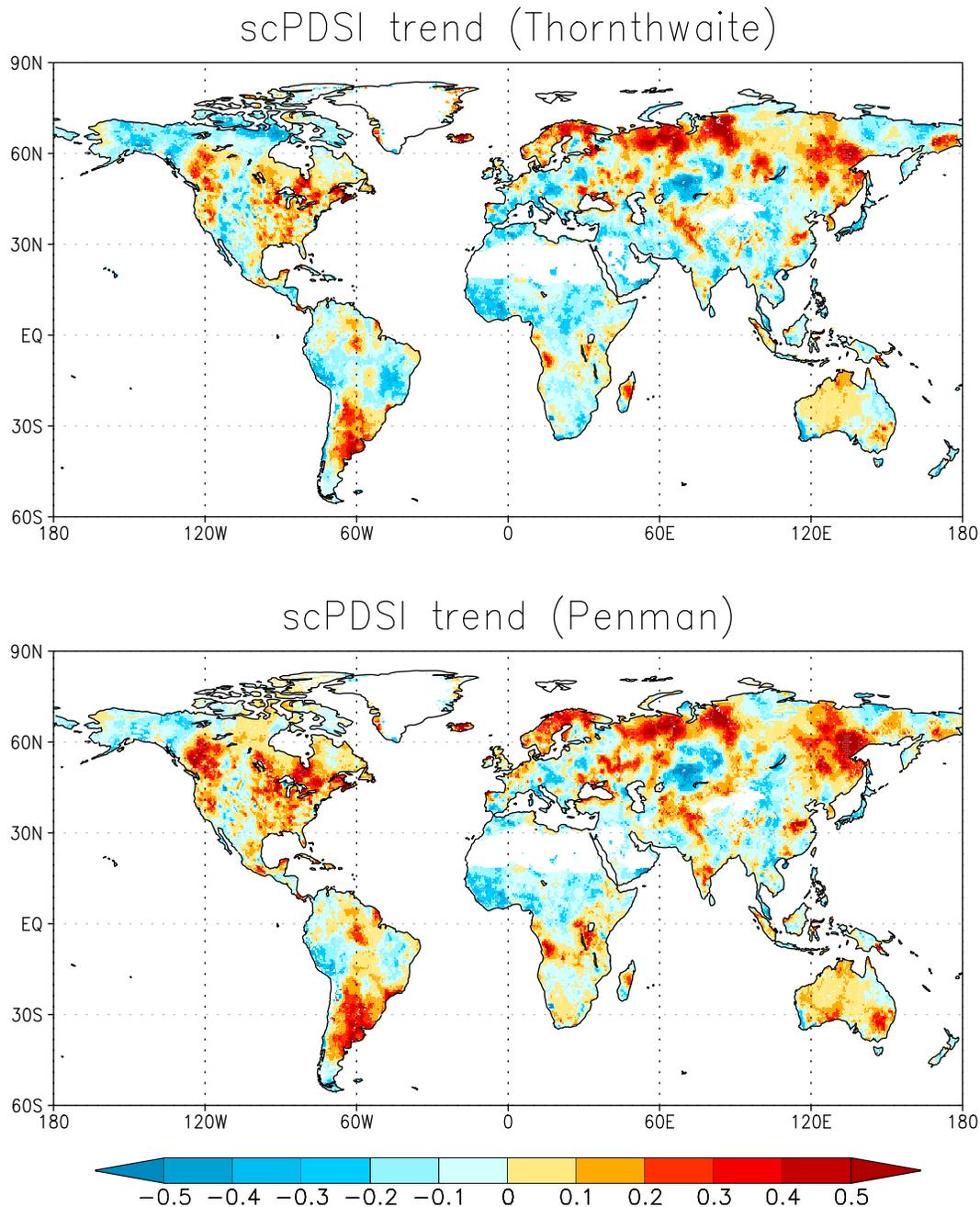


Figure 3. The trend values of annually averaged self-calibrating PDSI using the (top) Thornthwaite and (bottom) Penman-Monteith parameterization for PET. Trends are given in PDSI units per 10 years. Values calculated over the 1901–2006 period.

2.3.2. Penman-Monteith

[20] Potential evapotranspiration is generally thought to be more realistically estimated using Penman-type approaches. Here we use the parameterization developed by the Food and Agricultural Organization (FAO) [Allen *et al.*, 1994b; Ekström *et al.*, 2007]. This defines the reference or potential evapotranspiration as the rate of evapotranspiration from a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, com-

pletely shading the ground and with adequate water [Allen *et al.*, 1994b]. The formula for the FAO PET parameterization is

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)}. \quad (8)$$

The various inputs to this formula are explained in Table 2.

[21] In the absence of a data set with monthly mean wind speed measurements from 1901 onward, we take the gridded 1961–1990 monthly normals for wind speed provided by

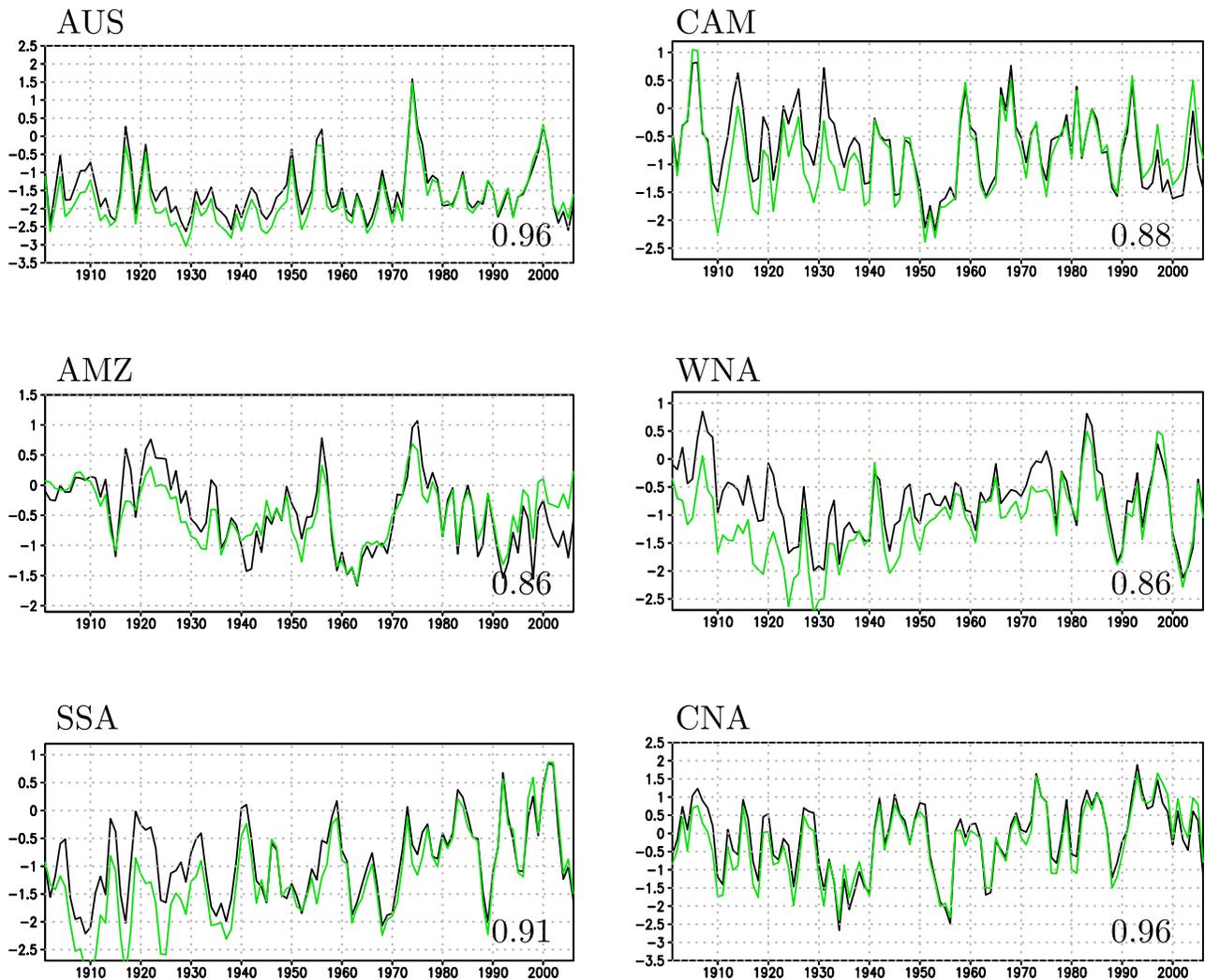


Figure 4. Time series of annually averaged self-calibrating PDSI (scPDSI) values, averaged over the regions Australia (AUS), Amazon Basin (AMZ), Southern South America (SSA), Central America (CAM), Western North America (WNA), Central North America (CNA), Eastern North America (ENA), Alaska (ALA), Greenland (GRL), Mediterranean Basin (MED), Northern Europe (NEU), Western Africa (WAF), Eastern Africa (EAF), Southern Africa (SAF), Sahara (SAH), Southeast Asia (SEA), East Asia (EAS), South Asia (SAS), Central Asia (CAS), Tibet (TIB), and North Asia (NAS). Black (green) lines denote the averages of scPDSI values calculated using the Thornthwaite (Penman-Monteith) formula for PET. The numbers in the lower right-hand corner of each plot give the Pearson correlation between the two scPDSI data series. The vertical axes denote the area-averaged scPDSI value. The horizontal axes denote time (years AD).

the Climatic Research Unit [New *et al.*, 2000], reduced from the 10 m measurement height to 2 m using the logarithmic wind profile, and use these values as proxy values for the monthly winds. The soil heat flux for monthly values is related to monthly mean of daily averaged temperatures of the preceding and following months [Allen *et al.*, 1994b, equation 5.17]. The slope of the vapor pressure curve, Δ , is calculated based on the saturation vapor pressure and the monthly mean of daily averaged temperatures. The net radiation at the crop surface, R_n , is calculated as the difference between short-wave radiation and the long-wave radiation. The first is related to monthly averages of cloud cover and monthly averages of daily total extraterrestrial

radiation. The latter is based on a grey body radiation, using as input both monthly averages of daily minimum and daily maximum temperatures, effective emissivity of the atmosphere (related to relative humidity), emissivity by the vegetation and an adjustment for the cloud cover.

2.3.3. Global Vegetation Cover

[22] When calculating potential evapotranspiration, based either on the Thornthwaite or the Penman-Monteith approach, the vegetation cover is taken to be globally uniform. Thornthwaite [1948] did not explicitly include any crop characteristics in his parameterization. Instead, he obtained his relationship by regressing measured monthly surface air temperature and the duration of daylight with measured

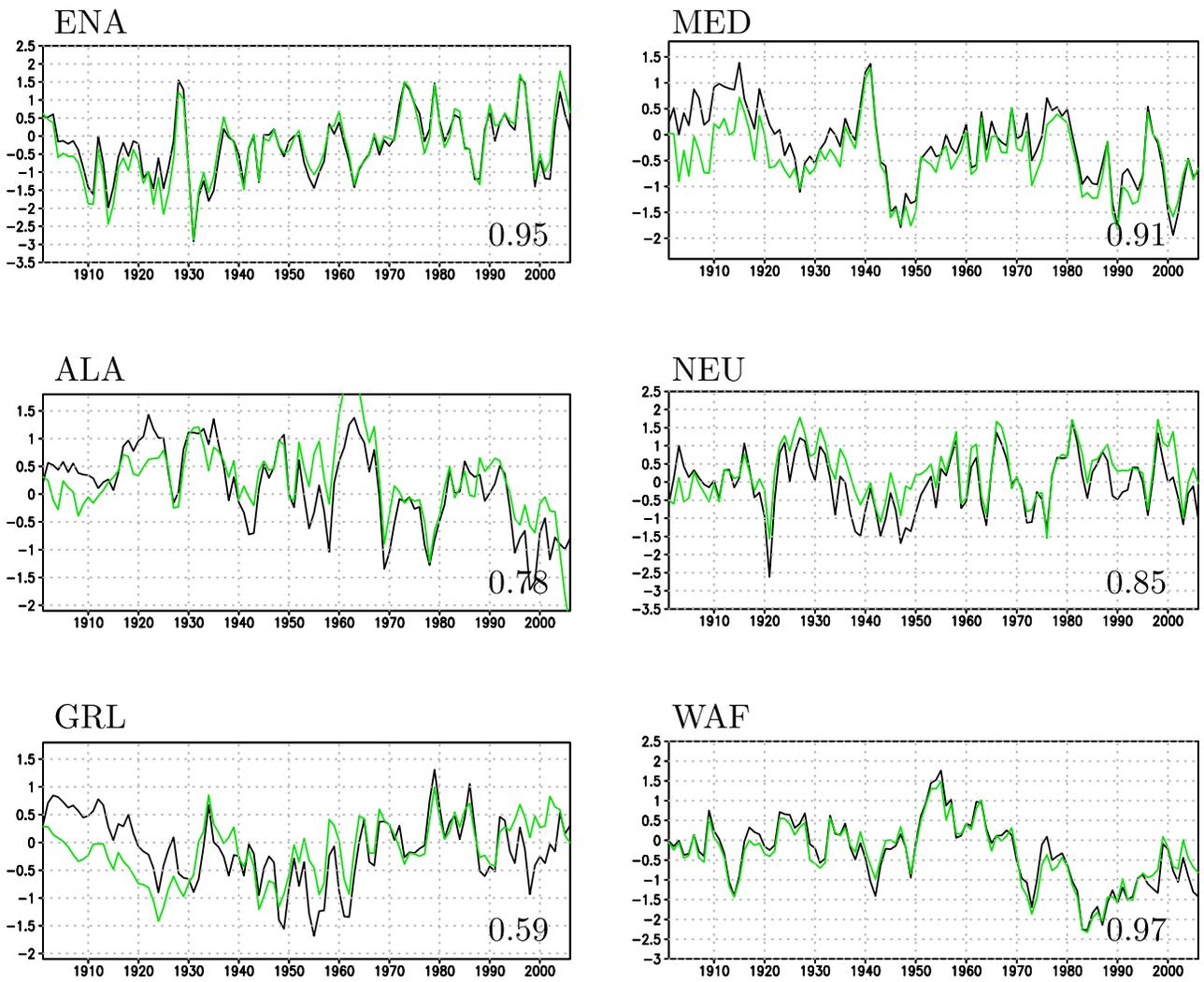


Figure 4. (continued)

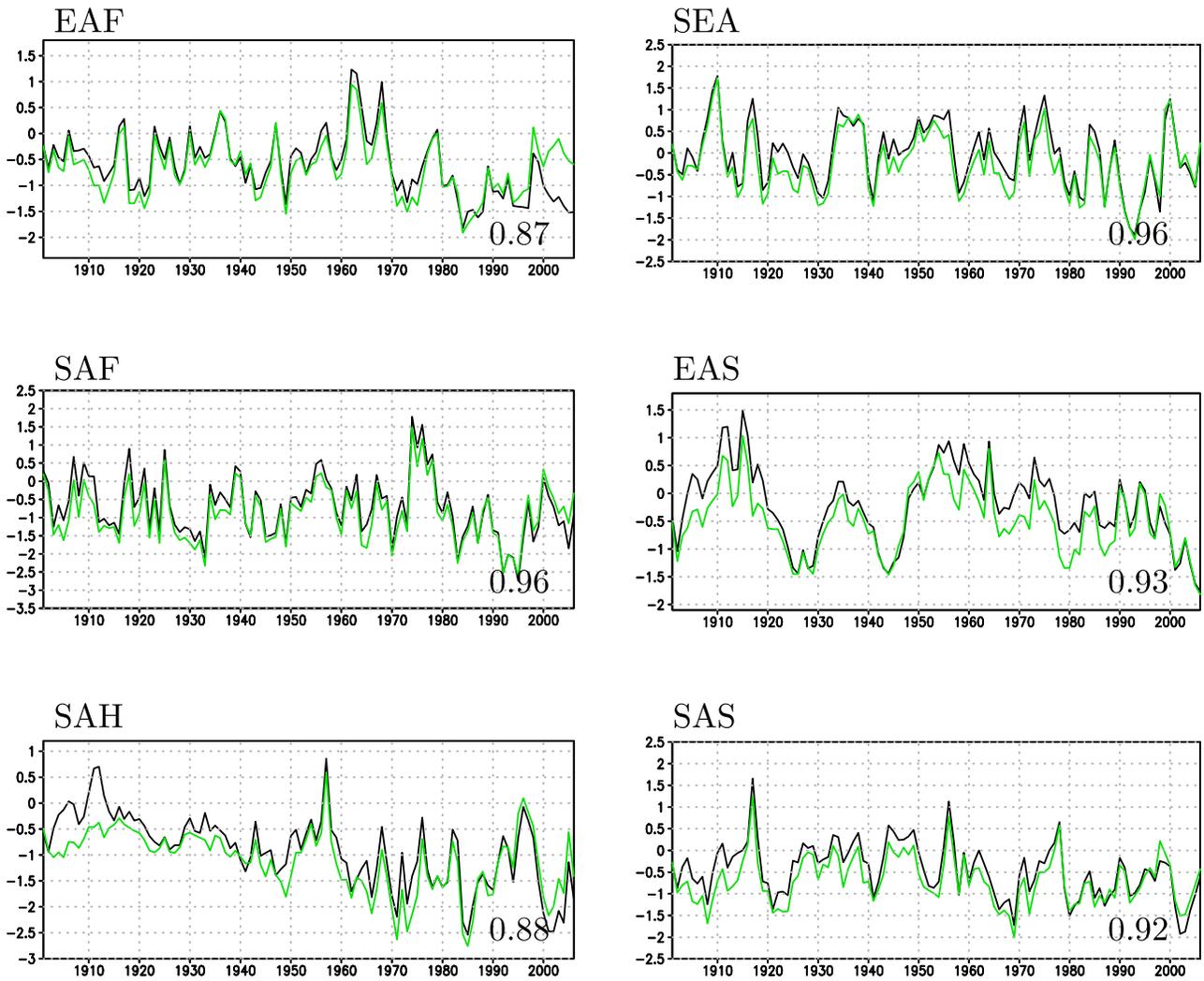


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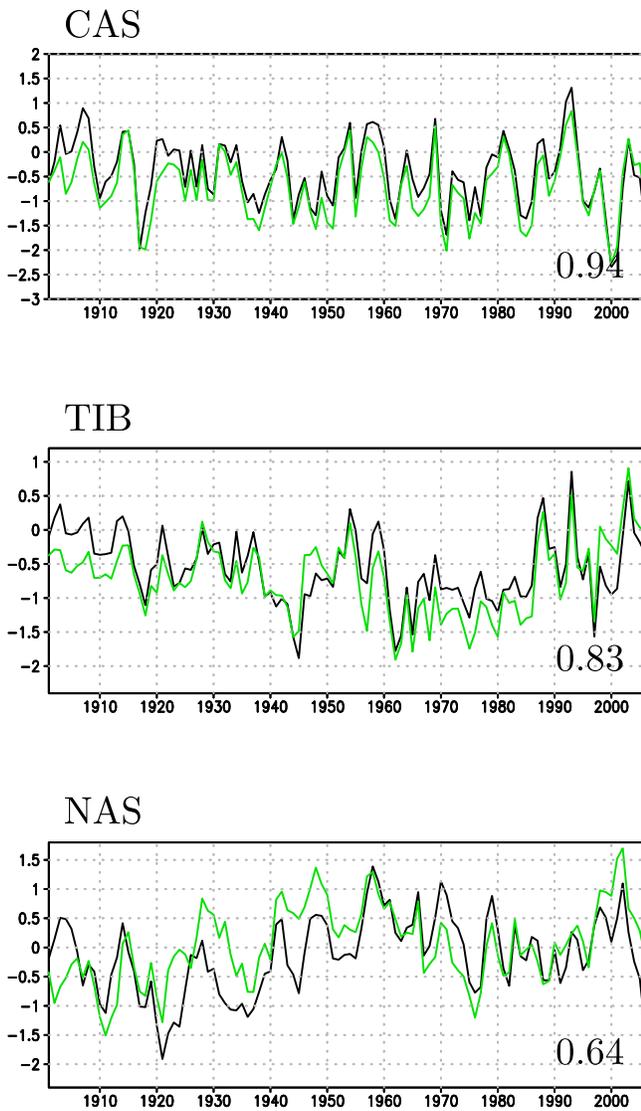


Figure 4. (continued)

monthly evapotranspiration from some well-watered grass-covered lysimeters in the eastern and central USA [Willmott *et al.*, 1985, p. 592]. The assumption of a uniform surface coverage is thus made implicitly in the Thornthwaite parameterization. For the Penman-Monteith approach the concept of a reference evapotranspiration is used, where a standardized surface roughness and bulk surface resistance parameters are used to represent a hypothetical grass surface. This approach for the Penman-Monteith parameterization is widely accepted in field practice and in research [Allen *et al.*, 1994a]. In contrast to the Thornthwaite formula, the Penman-Monteith parameterization does allow for a more tailored approach to include global variations in surface vegetation since it explicitly includes parameters which describe the vegetation characteristics. Note that the parameterization used here (equation (8)) is not the Penman-Monteith equation as such, since the latter equation has a broader applicability [Shuttleworth, 1992]. Rather, equation (8) is an implementation of the Penman-Monteith equation in which the several resistances are related to specific, well-defined, reference surfaces [Shuttleworth, 1992, section 4.2.5]. Nevertheless,

we use the reference grass surface in the Penman-Monteith equation for estimating PET since the critique on the use of the Thornthwaite parameterization relates to the absence of a more physically based PET estimate, and not to its inability to faithfully represent PET for various crop surfaces [Trenberth *et al.*, 2007, p. 261]. A more realistic global estimate of the Penman-Monteith PET would require inclusion of a global map of vegetation characteristics.

3. Results

[23] Comparing the values of PET using the Penman-Monteith parameterization and the Thornthwaite parameterization (Figure 1) shows that the two estimates can be vastly different. Figure 1 (left) shows the mean difference in annually accumulated values of PET using the Penman-Monteith approach minus the Thornthwaite-based estimate. It shows that in the tropics, the Thornthwaite method gives much higher values than the Penman-Monteith approach, whereas the opposite is the case for the subtropics. At higher latitudes, the relative differences in the means of the annually accumulated values between the two estimates are smaller. The Figure 1 (right) day shows zonally averaged values of the Penman-Monteith PET.

[24] The comparative overestimation of PET by the Thornthwaite parameterization in the tropics and its underestimation in the subtropics must be related to the simplicity of this parameterization. The overestimation is likely associated with the exclusion of cloud cover and vapor pressure deficit (which relates to the capacity of the air to take up water) in this parameterization, both of which will act to suppress high values of PET in the tropics. In the subtropics, the reverse is the case.

[25] Note that the values over Greenland in Figure 1 are artificially high; the Thornthwaite parameterization sets PET to zero for below-freezing temperatures, whereas the Penman-Monteith parameterization still allows for some PET.

[26] Despite the large differences in estimates for PET between the two parameterizations, the scPDSI values based on the two PET estimates are remarkably similar. Figure 2 shows the point correlations between annually averaged scPDSI values based on the two PET parameterizations. The correlations are greater than 0.8 for nearly 80% of the grid

Table 3. Fraction of Months for Which the Thornthwaite-Based Palmer Drought Severity Index (PDSI) is in the 10 Classes, Given That the Penman-Monteith-Based PDSI Indicates an Extremely Wet Month, $PDSI \geq 4$ ^a

	Fraction
$PDSI \geq 4$	0.62
$3 \leq PDSI < 4$	0.28
$2 \leq PDSI < 3$	0.05
$1 \leq PDSI < 2$	0.01
$0 \leq PDSI < 1$	0.01
$-1 < PDSI \leq 0$	0.01
$-2 < PDSI \leq -1$	0.02
$-3 < PDSI \leq -2$	0.07
$-4 < PDSI \leq -3$	0.26
$PDSI \leq -4$	0.60

^aResults are averaged over Europe, 35°N–70°N and 10°W–60°E, and calculated using data over the 1901–2006 period.

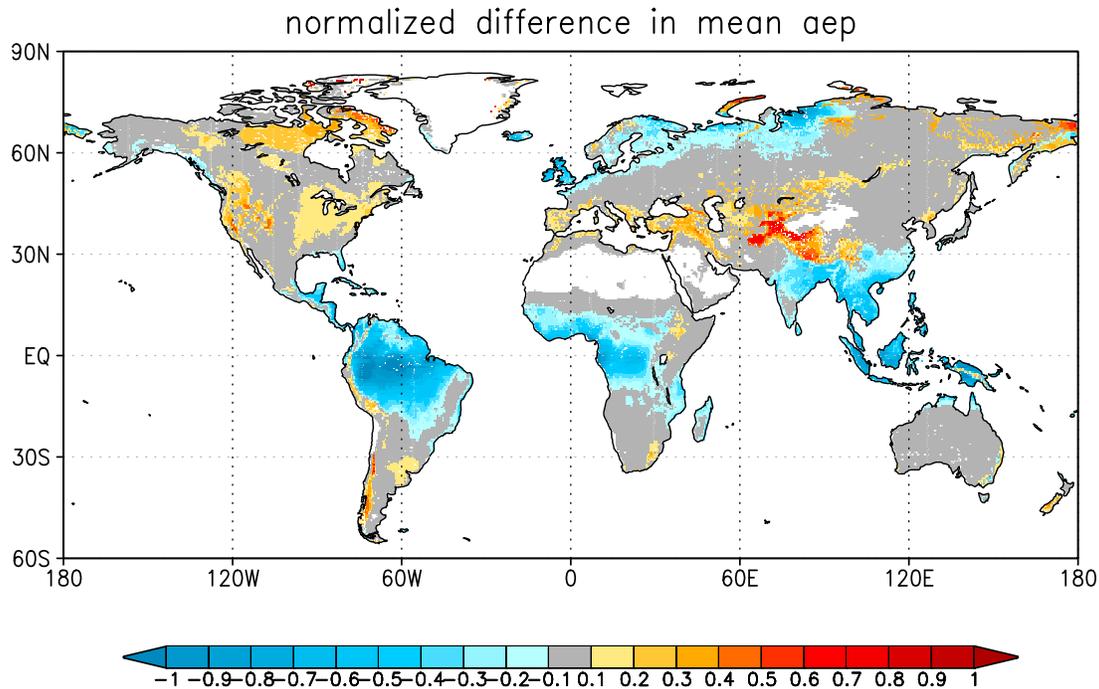


Figure 5. Mean values of the difference in annually accumulated values of actual evapotranspiration calculated from Palmer’s [1965] simple water balance model, where the water balance model is driven by PET values based on the Penman-Monteith formula minus PET values using the Thornthwaite formula. The mean difference is normalized with actual evapotranspiration values using the Penman-Monteith PET formula. Values calculated over the 1901–2006 period.

boxes, including many areas where the differences in the means of annually aggregated PET values show large differences. Areas where correlations are relatively low are Alaska and parts of the Canadian arctic, northern Asia and a modest area in South America.

[27] Figure 3 shows trends in annually averaged scPDSI values based on the Thornthwaite and Penman-Monteith PET parameterizations evaluated over the 1901–2006 period. These trends have not been tested for statistical significance. The patterns are broadly similar with perhaps the largest differences in the Canadian arctic, where there is a difference in sign. Other areas which show relatively large differences in trend values are western Canada, parts of South America and eastern Siberia. Nevertheless, Figure 3 indicates that the trend in PDSI is largely unaffected by the choice of PET parameterization. The same conclusion was reached recently also by Dai [2011], albeit using different precipitation and potential evaporation data sets.

[28] Figure 4 shows averages of annually averaged scPDSI values for the 21 regions defined by Giorgi and Francisco [2000], for both the scPDSI calculations based on the Thornthwaite PET parameterizations (black) and the Penman-Monteith PET parameterization (green). Figure 4 shows a remarkable similarity for all regions including those with more extreme climates. Extremely dry years, like the driest year on record for Northern Europe, 1921 [van der Schrier et al., 2006a], is reproduced in both scPDSI data sets.

[29] Given that Palmer’s classification of droughts is based on threshold values, the question arises as to whether an extremely dry month calculated using scPDSI values

based on the Penman-Monteith PET parameterization also classifies as an extremely dry month in the Thornthwaite-based scPDSI data set. Table 3 show that this is the case for both extremely dry and extremely wet months for Europe (35°N–70°N, 10°E–60°E), which is used here as an example. Values for other regions show similar agreements. The percentage of months which are in the extremely dry (wet) category for the Thornthwaite-based scPDSI data set, given that the Penman-Monteith based scPDSI data set indicates an extremely dry (wet) month, is 62% (60%). The areas where a mismatch in indication of an extremely dry or wet month is most common, are again Alaska, the Canadian arctic and northern Asia.

[30] There are two reasons for the insensitivity of the PDSI to differences in estimates of PET. One mechanism is found to be at work in areas which are relatively dry and where actual evapotranspiration is strongly limited by the amount of moisture in the soils. The other mechanism is at work in areas where potential and actual values of evapotranspiration are more balanced. The two different mechanisms are analyzed below.

4. Analysis

4.1. Similar Estimates of Actual Evaporation

[31] In areas where the actual evapotranspiration (AET) is limited by a lack of moisture in the soils, the actual evapotranspiration value will be much less than its potential value. This means that the levels of actual evapotranspiration are related more strongly to the intensity of precipitation rather than to the potential evapotranspiration levels.

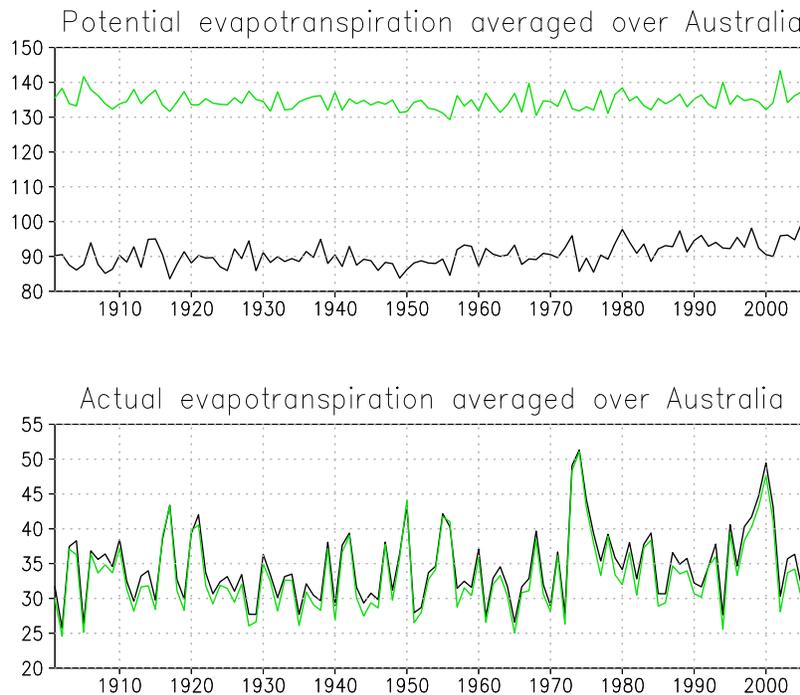


Figure 6. (top) Annually averaged values of PET, averaged over the Australian continent, based on the Thornthwaite (black line) and the Penman-Monteith formula (green line). The correlation between the series is 0.51. (bottom) The actual evapotranspiration as calculated by Palmer's simple water balance model, with the Thornthwaite-based (black line) and the Penman-Monteith-based (green line) potential evapotranspiration estimates as input. The correlation between the series is 0.99. Evapotranspiration is shown in mm/month.

Consequently, the sensitivity of the actual evapotranspiration to a change in the estimate of PET will be low. This is illustrated by calculating AET from the *Palmer* [1948] water balance model driven by precipitation and the Penman-Monteith- or Thornthwaite-based estimates of PET. Figure 5 shows that the grey areas have differences in AET less than 10% of the Penman-Monteith-based values of AET. With AET values insensitive to the PET estimate used, the water balance which is at the heart of the PDSI algorithm does not change. A comparison with Figure 1 shows that many of the areas with small differences in AET are characterized by large differences in PET.

[32] To illustrate this, the actual evapotranspiration, as calculated by Palmer's simple water balance model, is analyzed with a focus on Australia which is a region where the limitation of actual evapotranspiration is particularly clear. In Australia the two estimates of annually accumulated PET have very different mean values (Figure 1), where the Thornthwaite-based PET underestimates the Penman-Monteith estimate by 30% or more over 71.4% of the continent. For 27.4% of the Australian continent, this underestimation reaches 40%. Only for the northern and eastern coastal regions do the two PET estimates have means which are more similar, or where the Thornthwaite estimate overestimates the Penman-Monteith estimate (in the most northerly parts). However, a similar analysis for actual evapotranspiration, rather than its potential value (Figure 5), shows that the means of AET are actually very similar, despite the vast differences in their potential values. Over nearly the whole continent, the estimates of AET are less than 10% apart (Figure 5),

with approximately 77% of this area having estimates of AET less than 2% apart. A further illustration of the divergence of actual evapotranspiration from its potential value is provided by Figure 6, where time series of annually averaged PET estimates are given, averaged over Australia, for both the Thornthwaite and the Penman-Monteith parameterizations. The large difference in PET levels between the two estimates is evident (Figure 6, top) as well as the similarity of the annually averaged actual evapotranspiration values, averaged over Australia (lower panel). This confirms the first assertion mentioned in the previous paragraph. Averaged over the Australian continent, the correlation between the two PET estimates is 0.51, satisfying the second assertion.

[33] This analysis supports the conclusions of earlier work by *Hobbins et al.* [2008], who concluded that trends in water-limited regions are driven by precipitation trends and not by PET.

4.2. Similar Estimates of CAFEC Precipitation

[34] Figure 5 shows that there are also many areas where the differences in actual evaporation, using the two estimates of PET, are not small. In these areas, one can expect a shift in the water balance calculations which produce differences in the four constituents of the CAFEC precipitation (equation (1)) when using the Penman-Monteith or Thornthwaite PET estimates. This is confirmed in Figure 7, which shows the difference in mean annual values of these constituents as calculated using the Penman-Monteith PET minus the Thornthwaite PET. Figure 7 also shows that the difference in the contribution of evaporation (αPE) is

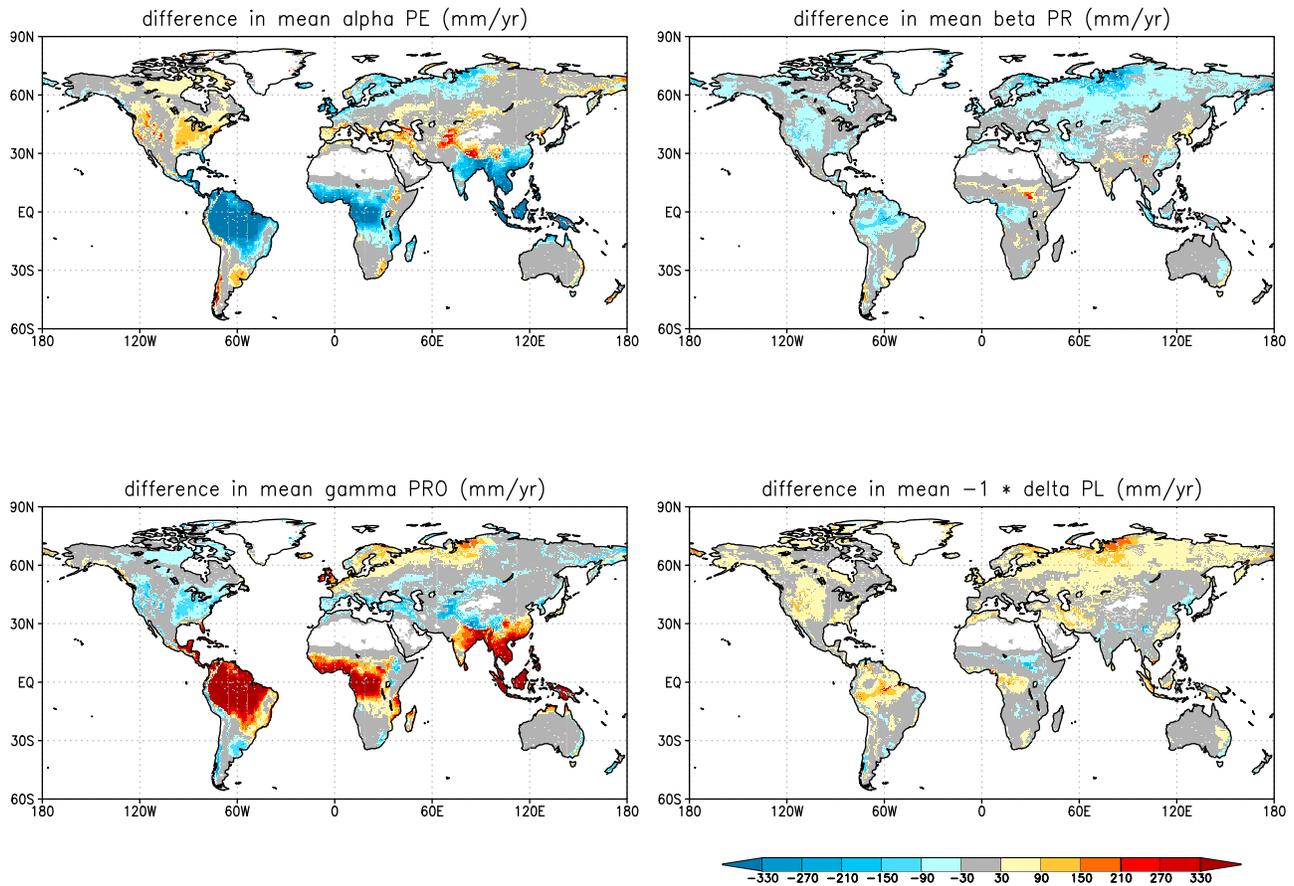


Figure 7. Differences in mean values of the four terms that contribute to the CAFEC precipitation (equation (1)). The αPE relates to the influence of potential evapotranspiration, βPR relates to recharge to the soils, γPRO relates to runoff, and δPL relates to the loss of moisture from the soils. The latter term is inverted for convenience. Values are calculated over the 1901–2006 period.

balanced by that of runoff (γPRO), and that differences in recharge to the soils (βPR) are balanced by differences in the loss ($-\delta PL$). Indeed, when the differences in mean values of annually averaged CAFEC precipitation is calculated (Figure 8), then large parts of the globe show small differences. The observed insensitivity of the CAFEC precipitation to a redistribution of the terms in the water balance can be explained by the construction of the CAFEC precipitation itself. *Palmer* [1965, p. 14] constructed this term in such a way that the long-term mean of the CAFEC precipitation is equal to the long-term mean of the actual precipitation. Since the water balance models are driven by the same actual precipitation, the long-term mean CAFEC precipitation needs to be similar despite differences in the estimates of PET.

[35] In Figure 9 this is taken one step further by correlating the two versions of annually averaged moisture anomaly d (equation (2)), based on the Penman-Monteith PET and based on the Thornthwaite PET. The moisture anomaly is the difference between the actual and the CAFEC precipitation and the overall high correlations in Figure 9 show, at least for annual averaged values, that the CAFEC precipitation is insensitive to the actual PET values used, despite the reorganization of the terms in the water balance from which it is calculated. The exceptions to this conclu-

sion are shown in the same isolated areas identified earlier (section 3) where the two PDSI estimates disagree. In fact, the correlation map of Figure 2 is a near perfect reflection of that of Figure 9.

4.3. Similar Estimates of the Climatic Characteristic

[36] The coefficient K' (equation (3)) used in *Palmer's* original PDSI changes only modestly when the Penman-Monteith PET estimate is replaced by the Thornthwaite estimate. For 82.8% of the land surface, the mean difference in annually averaged K' values is less than 10% of those based on the Penman-Monteith PET parameterization. These percentages drop to 67.0% (41.1%) when the threshold value is lowered to 5% (2%). With the potential evapotranspiration as input to the calculation of K' (3), the largest differences can be expected over areas with the largest discrepancies in PET estimates. For Australia, which has large differences in the estimates of PET, the relative difference in K' , averaged over the continent, is 10.9%.

[37] Input to the PDSI algorithm is the climatic characteristic; a modification of K' . For the self-calibrating PDSI the differences in the climatic characteristic K when using the Thornthwaite or Penman-Monteith parameterization for PET are smaller than the differences found in K' . For example, the relative difference in the climatic characteristic

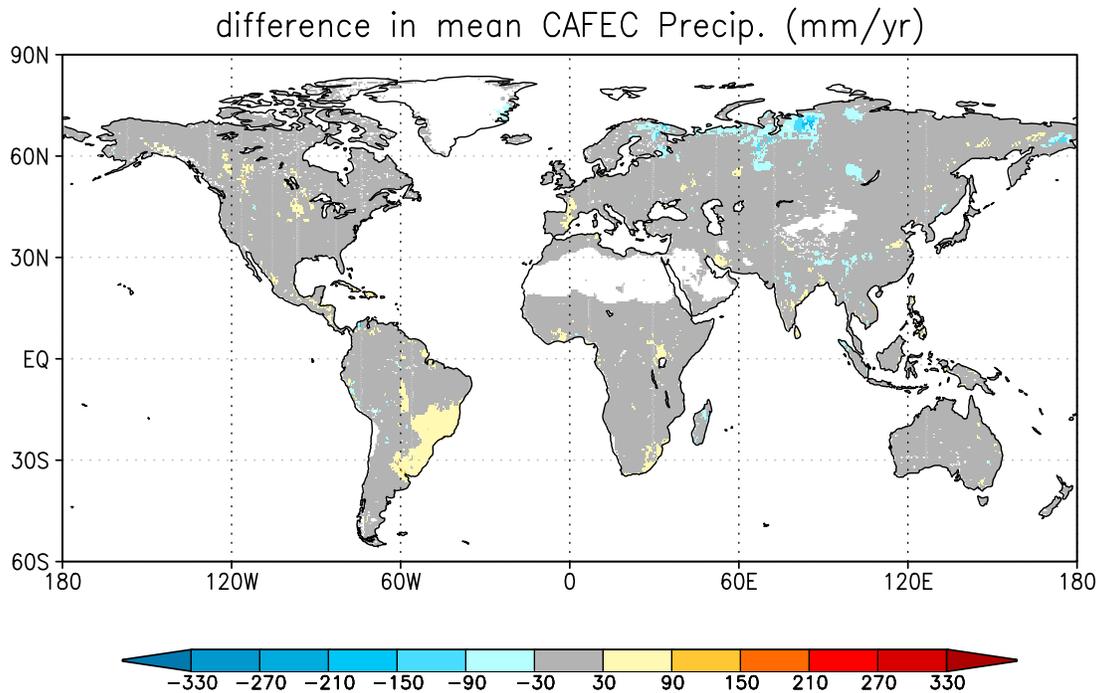


Figure 8. Differences in mean values of the CAFEC precipitation (equation (1)) which is at the heart of the PDSI calculations. Values are calculated over the 1901–2006 period.

K averaged over Australia is considerably lower than that of K' at 5.7%.

4.4. Observed Differences

[38] Those areas where the temporal variability of PDSI forced with Penman-Monteith PET is very different from

that forced with Thornthwaite PET (Alaska, the Canadian arctic and northern Asia, Figure 2) are the same regions where the two alternative estimates of the CAFEC precipitation (equation (1)) show low temporal correlation. Apparently, the water balance in these regions is distorted to the point that temporal variations in the CAFEC precipitation are

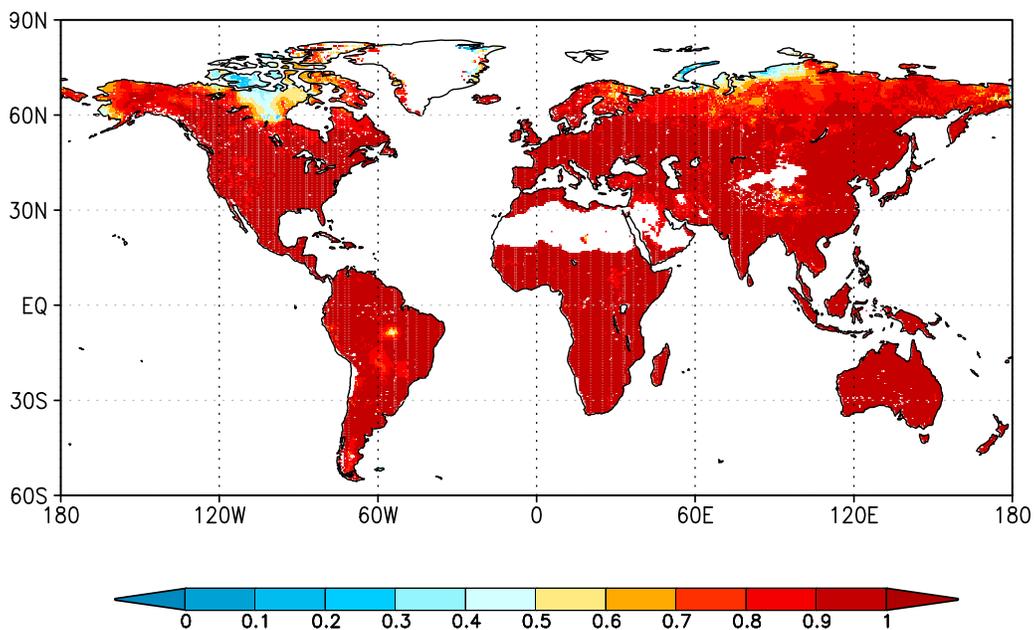


Figure 9. Point-by-point correlation of yearly averaged values of the moisture anomaly d (equation (2)), based on a water balance using the Thornthwaite parameterization of PET and the Penman-Monteith parameterization of PET. The moisture anomaly d is the difference between the actual precipitation and the CAFEC precipitation. Correlations are for the 1901–2006 period.

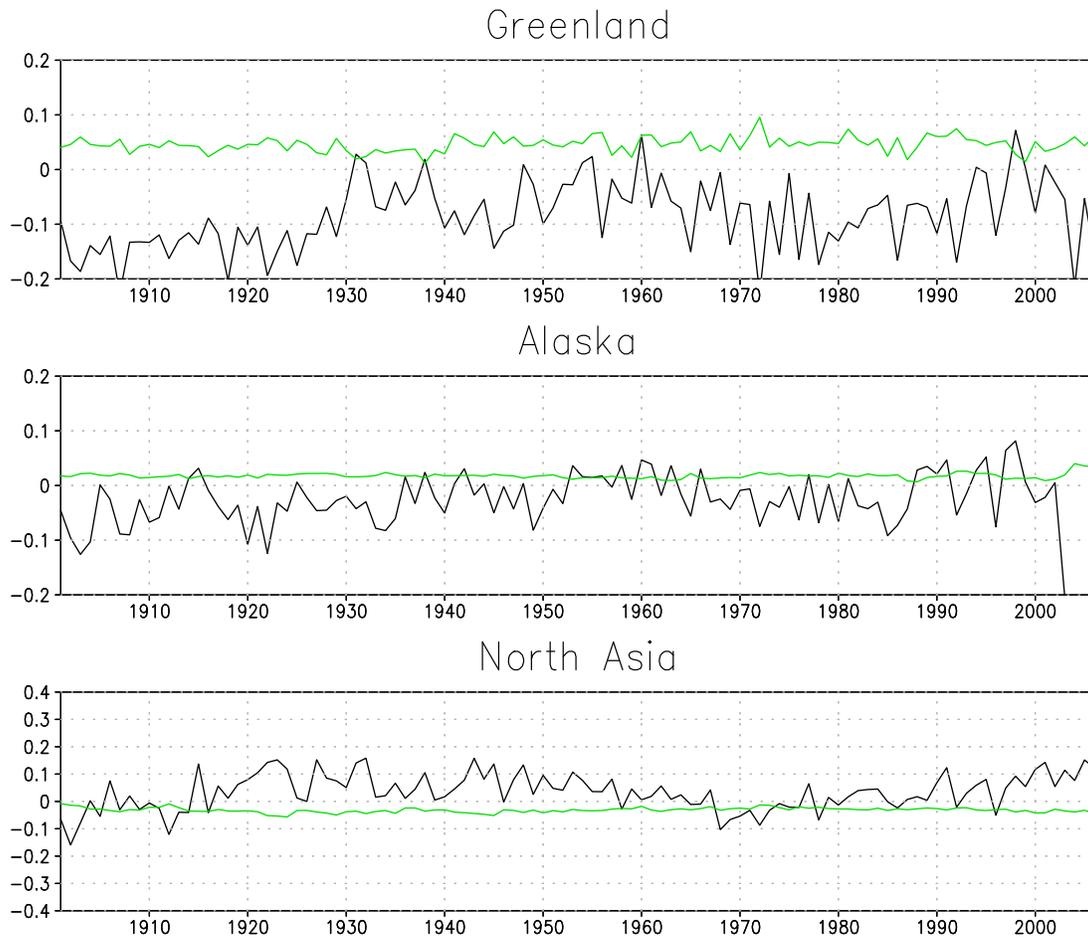


Figure 10. Time series of yearly averaged values of the contribution of potential evapotranspiration αPE (black line) and potential runoff γPRO (green line), which are the contributions of potential evapotranspiration and runoff to the CAFEC precipitation (equation (1)), respectively, averaged over the *Giorgi and Francisco* [2000] regions Greenland (which includes the Canadian arctic), Alaska, and north Asia.

different when based on the Penman-Monteith or the Thornthwaite PET. This is confirmed in Figure 10, which shows for the regions Alaska, Greenland (including the Canadian arctic) and northern Asia the differences in the Penman-Monteith and Thornthwaite based αPE and γPRO , which enter the formula for the CAFEC precipitation (equation (1)). It is clear from Figure 10 that these terms are not anticorrelated for the three regions shown and that variations in these terms do not balance each other in the CAFEC precipitation. The definition of the regions used follows that of *Giorgi and Francisco* [2000].

[39] The area-averaged scPDSI time series in Figure 4 show that for nearly all regions the scPDSI values based on the Penman-Monteith PET are systematically lower than the Thornthwaite-based scPDSI values for the years prior to approximately 1950. This is particularly apparent for Western North America (WNA) and to a lesser extent also for Australia (AUS), Central North America (CNA), Southern South America (SSA) and the Mediterranean (MED). A similar offset for these few decades is found in area-averaged annual values of the CAFEC precipitation. The area-averaged PET estimates have been calculated for the above selection of regions. Figure 11 shows the results for Western North America and the Mediterranean basin.

This analysis shows that for the first few decades, the difference between the Penman-Monteith and the Thornthwaite PET estimates is larger than for the more recent decades. The calibration period used in this study is 1951–2006 (section 2.1) so the CAFEC precipitation balances the actual precipitation over this period. Any additional offset in either the Thornthwaite or the Penman-Monteith PET for the early parts of the record compared to the calibration period, will be expected to produce some divergence in CAFEC precipitation compared to the actual precipitation, as is seen in the few early decades.

5. Discussion and Conclusions

[40] There are vast differences in annually accumulated values of potential evapotranspiration (PET) as calculated using the *Thornthwaite* [1948] parameterization or the FAO-endorsed Penman-Monteith parameterization [*Allen et al.*, 1994b; *Ekström et al.*, 2007]. However, calculating scPDSI using the two PET estimates gives very similar results, in terms of correlation, regional averages, trends and in terms of classifying extremely dry or wet months. Temporal variations in the PDSI are largely controlled by variations in precipitation rather than potential evapotranspiration [*Guttman*,

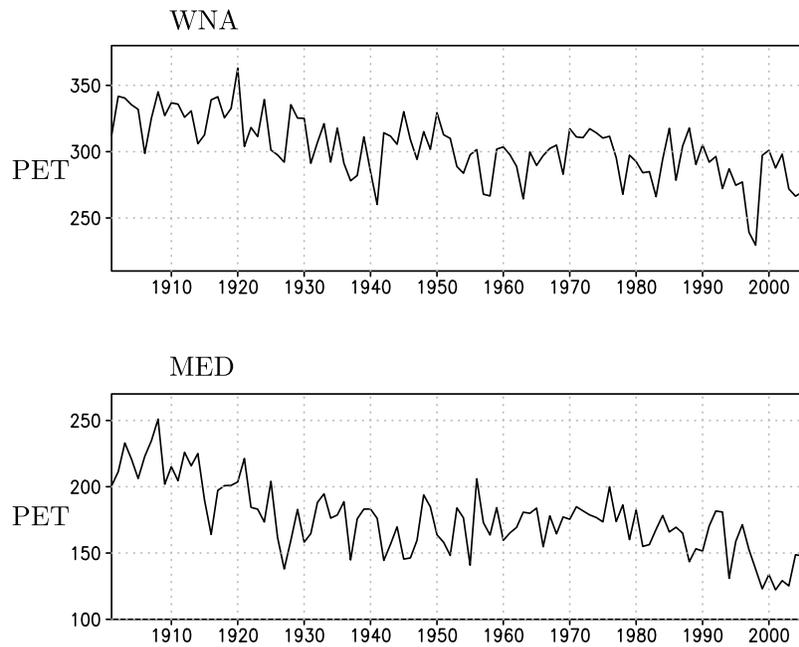


Figure 11. Time series of yearly averaged values of the difference between the area-averaged potential evapotranspiration based on the Penman-Monteith parameterization and the Thornthwaite parameterization. Data averaged over (top) Western North America and (bottom) the Mediterranean basin. Regions are defined following *Giorgi and Francisco* [2000].

1991]. The principal reasons for this are related to what *Palmer* [1965] termed the Climatically Appropriate For Existing Conditions (CAFEC) precipitation. For moisture stressed areas of the world, *Palmer's* simple water balance model shows that actual evapotranspiration is not a reflection of its potential value but of precipitation amount. For these areas, the water balance is insensitive to the overall level of the potential evapotranspiration and we find that the amplitude of the PET estimate has little influence on the moisture anomaly metric used in the PDSI algorithm for these areas. This is consistent with the earlier findings of *Hobbins et al.* [2008].

[41] The decoupling of the potential and actual evapotranspiration observed in moisture stressed areas, is reminiscent of the complementary relationship between these two, first formulated by *Bouchet* [1963] and further developed by *Morton* [1965]. This relationship states that AET declines as PET increases due to a negative feedback between evaporation and evaporative demand [*Brutsaert*, 1982]. Based on this relationship, the areas with high PET values are expected to have low AET, which is indeed observed in this study (Figure 1).

[42] The second reason for the insensitivity of the PDSI to either the Thornthwaite or Penman-Monteith PET comes into play in areas that do not experience significant moisture stress. Here we find a redistribution in the water balance which leaves the CAFEC precipitation largely unaffected by the two different estimates of PET. The reason for this is that by construction, the CAFEC precipitation is required to match the long-term mean of the actual precipitation and the water balance is reshuffled to meet this requirement when one PET estimate is replaced by the other. It is shown in this study that this not only holds for the long-term mean, but also for the year-to-year variations over the greater part of

the land surface. The areas where the Thornthwaite-based scPDSI and the Penman-Monteith-based scPDSI diverge, are the same areas where the temporal variations in the associated CAFEC precipitation diverge.

[43] Potential evapotranspiration also enters the calculation of a calibration coefficient in the PDSI algorithm and is potentially a way in which diverging estimates of PET can lead to diverging PDSI estimates. However, it turns out that this calibration coefficient, the climatic characteristic, shows only minor changes even when the two PET estimates are very different.

[44] The calculation of the climatic characteristic is modified in the algorithm of the self-calibrating PDSI compared to that of the original PDSI, although they have a common basis. It must be noted that this modification in the scPDSI will reduce the impact of changing levels of PET compared to the effect on the original PDSI. Furthermore, due to the absence of a gridded global data set for monthly averages of wind strength, climatological values were used as a proxy. A possible “stilling” trend [*Vautard et al.*, 2010] in wind will not have an effect on Penman-Monteith PET values used in this study.

[45] We have shown that vastly different estimates of PET do not lead to large changes in PDSI values because of the insensitivity of the CAFEC precipitation to the use of either the Thornthwaite or Penman-Monteith estimates of PET. The CAFEC precipitation is directly based on quantities derived from the water balance model, which is the backbone of the PDSI. This study reinforces the relevance of *Alley's* [1984] critique of the water balance model as used in the original PDSI calculations, indicating that a more realistic water balance model might affect the PDSI estimates.

[46] On a global scale, estimates of PDSI are to a large degree insensitive to the choice of which formula for potential

evapotranspiration is used. This argues against a recurrent circumspexion in interpreting large-scale analysis of changes in PDSI where they are based on *Thornthwaite's* [1948] parameterization of PET, such as those described in the IPCC AR4 [Meehl et al., 2007].

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