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Eighty years of meteorological observations at Wageningen, the Netherlands: precipitation and evapotranspiration

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ABSTRACT: Annual and seasonal characteristics of precipitation and evapotranspiration were analysed of an 80-year data record (1928–2008) at Wageningen (the Netherlands). The precipitation series shows a mean annual rainfall of 765 ± 130 mm with a relatively high interannual variability [coefficient of variation (CV) = 17.0%]. Both the annual and seasonal rainfall trends show a small but statistically insignificant increase. Potential evapotranspiration was estimated by Makkink's formula, using observations of incoming solar radiation and air temperature as inputs. This provides a mean evapotranspiration of (525 ± 50) mm annum^{-1} with a relatively low interannual variability (CV = 9.5%). The annual and seasonal trends appear to be statistically significant, except for the summer season. In addition, since 1992, actual evapotranspiration is measured by the eddy-covariance technique and these results were found to be highly correlated with the potential evapotranspiration ($E_{act} \approx 0.75 E_{pot}$). A comparison is made with a class A evaporation pan operating between 1984 and 1989. Copyright © 2009 Royal Meteorological Society

KEY WORDS precipitation; actual evapotranspiration; potential evapotranspiration; climate; class A pan; grassland

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1. Introduction

Standard meteorological observations at Wageningen University (51°58′N, 5°39′E) commenced in 1927, with precipitation measurements starting in 1920. If both precipitation and evapotranspiration in a given area are known, the water balance can be calculated.

Precipitation, the main term in the water budget, can easily be collected by a simple rain gauge. Determining evapotranspiration, however, is much more complicated. One of the first evaporation measurements were made with the so-called Piche atmometer (Piche, 1872). This is a glass tube filled with distilled water, closed at the bottom by blotting paper to mimic a leaf. Because free water is always available, this instrument reproduces evaporation numbers that are comparable with potential evapotranspiration calculations (De Vries and Venema, 1953; Stanhill, 1962; Jacobs and Linclaen Arriens-Bekker, 1983). Despite the atmometer being inexpensive, simple to use and easy to transport, it is not widely used in practice and especially not for long-term observations.

A second evaporation instrument widely used in hydrological practices is the class A evaporation pan (Himes, 1928; Penman, 1948; Wartena and Borghorst, 1961; Doorenbos and Pruitt, 1977). For a period of a week or more, this instrument also produces evaporation figures that are representative of potential evapotranspiration (Thom *et al.*, 1981; Jacobs *et al.*, 1998). At our Wageningen University observatory, the class A evaporation pan was used for a period of 6 years during the growing season (1984–1989). In wintertime, the water in the pan frequently froze, and as such the pan was often seriously damaged.

Apart from simple instruments, potential evapotranspiration can also be calculated by using meteorological parameters. Here, the best-known model is the open water model by Penman (1948). In Penman's model, two fluxes (net radiation and soil heat flux) and three variables must be known (air temperature, air humidity and wind speed), as well as a so-called crop factor, where this crop factor is a relation between open water evaporation and a given crop. In practice, the problem is that often the net radiation is not measured.

In the Netherlands, it is common to use Makkink's potential evapotranspiration approach (De Bruin, 1981; Rosenberg *et al.*, 1983), which is in fact a much simpler model. Only the incoming short-wave radiation, air temperature and a crop factor are required. In this model, the incoming global radiation is essential, but this quantity is measured more frequently than net radiation and, if not available, this quantity can also be estimated by relatively simple radiation models such as the classical model of Ångström (1924) using sunshine duration or alternatives that use cloudiness (e.g. Holtslag and Van Ulden, 1983).

The importance of observing the incoming solar radiation and the trends found for a mid-latitude coastal country has already been discussed in a companion

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paper (Jacobs *et al.*, submitted). For a mid-latitude coastal country as well as for the wet tropics, however, it has been shown that potential evapotranspiration is a realistic estimate for actual evapotranspiration (Jacobs and De Bruin, 1998). Since Makkink's potential evapotranspiration is mainly driven by the global radiation, then realistic estimates can be made of potential evapotranspiration and consequently also of actual evapotranspiration if the global radiation is known.

Presently, a standard way to estimate the actual evapotranspiration is to apply the eddy-covariance (EC) technique. This technique, however, cannot be used during rainy periods and during dewy nights (Jacobs *et al.*, 2006). Consequently, EC calculations must be used in conjunction with adequate gap filling of data. The gap-filling approach used in the present study is the so-called A-g_s model, where the A-g_s model is a process-based model that couples the photosynthetic assimilation, A, to leaf stomatal conductance, g_s (Jacobs and De Bruin, 1992; Ronda *et al.*, 2001; Jacobs *et al.*, 2007). An advantage of the A-g_s model is that the calculations are based on simple plant characteristics, for example, whether the vegetation uses a C3 or C4 metabolism (vascular plants are divided into two distinct groups, C3 and C4, based on their different CO_2 assimilating mechanisms), and on atmospheric variables that are measured on a routine basis at standard meteorological observation sites. For 16 complete years (1992–2008), the EC technique in combination with the A-g_s model results was applied to obtain estimates of actual evapotranspiration.

The objective of the present study is first to analyse the behaviour of precipitation during the last 80 years of our observation period. The second objective is to analyse Makkink's potential evapotranspiration data and to compare the obtained results with the class A evaporation pan as well as with actual evapotranspiration data using the EC technique.

2. Materials and methods

Meteorological weather observations at Wageningen University began in the backyard of our institute in 1927. An example of one of the first set-ups of the observatory is given in Figure 1, where the rain gauge can be seen. This rain gauge is a so-called tilting-siphon rain recorder as described in the Her Majesty's Stationery Office (1969). During the entire period, only two serious gaps in the data series occurred owing to the Second World War; in 1940 (from May 10 to May 20) and in 1945/1945 (from September 20 to June 30). Due to building activities in 1960, the measurement site was shifted to a new location, about 1 km west of the original plot just outside Wageningen (51°58′N, 5°38′E). Here, the observatory is surrounded by grassland only. A picture of the present measurement set-up is depicted in Figure 1. The turf wall grass rain gauge set-up in the centre of Figure 1 can clearly be seen.

During the growing season from March 1984 to October 1989 (6 years), evaporation was measured from the class A evaporation pan. The pan is made of stainless steel, diameter of 1.2 m, depth of 0.25 m and is mounted on a wooden open platform, 0.15 m above the ground. The pan is filled with tap water until about 50 mm below the brim. The net pan evaporation (evaporation minus precipitation) is estimated daily by measuring the water surface level with a special micrometer hook gauge with a precision of 0.1 mm. The hook gauge is placed in a still-well in the centre of the pan to provide an undisturbed water surface.

In various practical applications, the evapotranspiration of unstressed crops is estimated with the so-called crop factor approach (e.g. Doorenbos and Pruitt, 1977). In this approach, the evapotranspiration of unstressed optimally growing crops, E_{opt}, is calculated as follows:

$$E_{opt} = k_c E_{ref} \quad (1)$$

Figure 1. Left panel: overview of one of the first designs of the Wageningen University meteorological observatory. In the centre is the tilting-siphon rain recorder set-up. Right panel: overview of the current set-up of the observatory. In the centre is the turf wall grass rain gauge set-up. This figure is available in colour online at www.interscience.wiley.com/ijoc

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where k_c is a crop factor and E_{ref} (mm) is the evapotranspiration of a reference crop, which is usually grass. For grass, $k_c = 1$ by definition.

Makkink (1957) found that the daily average of the evapotranspiration of grass, with no shortage of water, is well described by (in energy units)

$$L_v E = c_1 \frac{s}{s + \gamma} K \downarrow + c_2 \quad (2)$$

where $K\downarrow$ (W m^{-2}) is the incoming global radiation, s (Pa k^{-1}) is the slope of the saturation water vapour temperature curve at air temperature, L_v (J kg^{-1}) is the latent heat of vaporisation, γ (Pa k^{-1}) is the psychometric constant and c_1 and c_2 are empirical constants.

De Bruin (1981, 1987) simplified expression (2) further to

$$L_v E = 0.65 \frac{s}{s + \gamma} K \downarrow \quad (3)$$

and found that Equation (3) yields reliable results for unstressed grass.

Combining Equations (1) and (3), we obtain a simple estimate for the evapotranspiration of unstressed crops:

$$L_v E = 0.65 k_c \frac{s}{s + \gamma} K \downarrow \quad (4)$$

Feddes (1987) presented crop factors, k_c, for different arable crops in the Netherlands. For grass, the crop factor is $k_c = 1$ throughout the year.

A lattice tower is instrumented with an EC system installed at a height of 4 m. This system included a three-dimensional sonic anemometer (3-D Solent Res. Gill Instruments Ltd., model A1012R2) and an open-path infrared CO_2 and H_2O gas analyser (IRGA) (LI-COR Inc. Lincoln Ne, model LI-7500). The three-dimensional sonic anemometer and the IRGA are placed together, at 0.05 m apart. The raw data of the EC system are stored on a computer and processed later, using a first-order recursive digital filter with a time constant of 200 s (McMillen, 1988). Here, a moving average is subtracted from every sample to get the fluctuating value of all the measured components. A software program (Van den Hurk, 1996) performed the necessary corrections, including coordinate rotation (McMillen, 1988), Webb corrections (Webb *et al.*, 1980) and frequency response corrections (Moore, 1986), required for calculating the half-hour averaged flux densities. More details can be found elsewhere (Jacobs *et al.*, 2003, 2007).

Gaps in actual evaporation data are filled with calculations according to an A-g_s model. The transpiration rate of a vegetation type, $L_v E$ (W m^{-2}), can be written as (Beljaars and Holtslag, 1991):

$$L_v E = \rho L_v \frac{\varepsilon}{p} \frac{g_a g_{c,w}}{g_a + g_{c,w}} D_s \quad (5)$$

where ρ (kg m^{-3}) is the density of the air, D_s (Pa) is the vapour pressure deficit at plant level, g_a (s m^{-1}) is the aerodynamic conductance, $g_{c,w}$ is the canopy conductance to water vapour, $\varepsilon = 0.622$ is the ratio of the molar masses of water vapour and dry air and p (Pa) is atmospheric pressure. The canopy conductance, $g_{c,w}$, is a complex relationship between plant characteristics and environmental variables and is calculated by using the A-g_s model. Details of this model can be found elsewhere (Jacobs *et al.*, 2007).

3. Results and discussions

Figure 2 contains the interannual courses of precipitation and evapotranspiration during the observation period between 1928 and 2008; the mean linear trends are also depicted. From the precipitation data, the annual mean precipitation was 765 mm with a standard deviation of 130 mm. The coefficient of variation (CV), which is the standard deviation divided by the mean value, is relatively high (17%). Based on Figure 2, the mean annual precipitation increased by about 6 mm per decade (0.8% per decade), which is relatively small. The wettest year was 1966 with 1162 mm and the driest year was 1977 with 450 mm.

The interseasonal course of precipitation during the observation period is contained in Figure 3, including the mean linear trends of the four seasons. The mean seasonal precipitation was, in winter season, 190 ± 60 mm with a CV of 31.6%, spring was 160 ± 50 mm with a CV of 31.3%, summer was 215 ± 70 mm with a CV of 32.6% and fall was 200 ± 60 mm with a CV of 30.0%. The winter season showed the highest increase with 3 mm per decade (1.6% per decade) and the summer season showed a decrease of about 2 mm per decade (-1.0% per decade).

As the annual and seasonal CVs in precipitation are very high, it is important to analyse the statistical confidence intervals of these trends in the precipitation as well. Table I contains the results of the statistical significance in the trends per decade and were found to be insignificant.

It is interesting to compare our findings with the results of the precipitation trend maps in the IPCC report (Trenberth *et al.*, 2007). This report shows that the

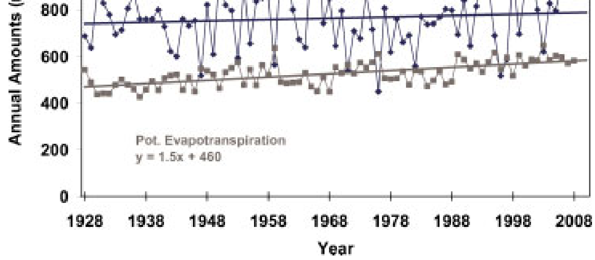

Figure 2. The courses of interannual precipitation and potential evapotranspiration, their trends and correlation coefficients during the observation period. This figure is available in colour online at www.interscience.wiley.com/ijoc

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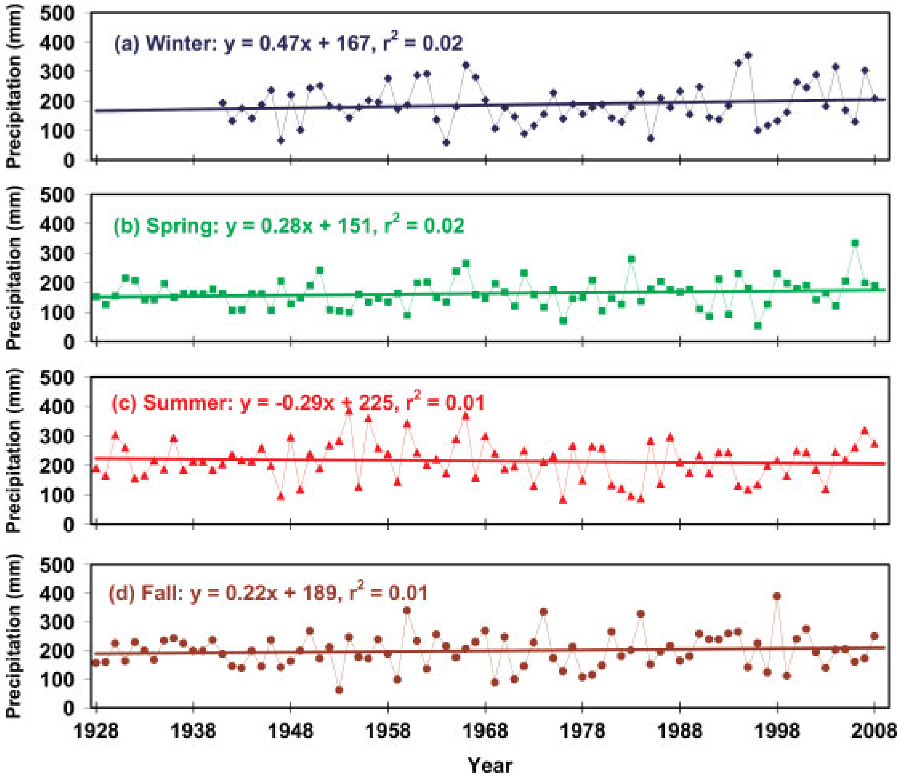

Figure 3. The courses of seasonal precipitation, their trends and correlation coefficients during the observation period. Winter, 1 December–1 March; Spring, 1 March–1 June; Summer, 1 June–1 September; Fall, 1 September–1 December. This figure is available in colour online at www.interscience.wiley.com/ijoc

Table I. The statistical significance results in the trends of the 10-yearly precipitation.

Season	Mean (mm)	Absolute trend (mm decade^{-1})	% decade^{-1}	Significance ($\alpha = 0.05$)
Year	765	$+5.80 \pm 12.21$	+0.8	No
Winter	190	$+3.00 \pm 5.66$	+1.6	No
Spring	160	$+2.98 \pm 4.47$	+1.9	No
Summer	215	-2.20 ± 6.21	−1.0	No
Fall	200	$+2.57 \pm 5.57$	+1.3	No

precipitation trend for 1900–2005 in Scandinavia gives a mean increased precipitation, decreased precipitation in the Mediterranean region and the Netherlands somewhere in-between. This result roughly agrees with the results in the present study. We also compared our Wageningen results with three other nearby stations in the Netherlands (Table II, Klein Tank *et al.*, 2002). Despite differences in the trends between the stations, the differences are statistically not significantly different.

Figure 2 also contains the interannual course of Makkink's potential evapotranspiration during the observation period 1928–2008. From the potential evapotranspiration calculations, the mean potential evapotranspiration was 525 ± 50 mm with a CV of 9.5%, which is much lower than the CV for precipitation. Moreover, Makkink's potential evapotranspiration increased by about 14 mm per decade (2.7% per decade), which is relatively high. It must be noted that the increase of potential evaporation is mainly caused by the increase in global radiation as found earlier (see, e.g. Equation (4) and Jacobs *et al.*, 2009).

Figure 4 contains the interseasonal courses of Makkink's potential evapotranspiration during the observation period and the mean linear trends of the four seasons during the observation period. The mean seasonal evapotranspiration was winter 30 ± 3 mm with a CV of 10.0%, spring 160 ± 20 mm with a CV of 12.5%, summer 250 ± 30 mm with a CV of 12.0% and fall 85 ± 10 mm with a CV of 11.8%. It is interesting to notice that the relative potential evapotranspiration change during the seasons is winter 1.9%, spring 3.7%, summer 2.5% and fall 0.6%.

The annual as well as the seasonal CVs in potential evapotranspiration is much lower than for precipitation. However, an analysis of the trends in the statistical confidence intervals is also of interest in this case, particularly as the 10-year trends are high. In Table III, the results of the statistical significance have been presented; both the annual and seasonal trends are statistically significant except for the summer season.

Figure 5 contains the mean annual distribution of precipitation and evapotranspiration throughout the year, along with their standard deviations. Precipitation is more or less evenly distributed throughout the year, except from February to April where precipitation is somewhat lower. Also it can be noted that the deviation of precipitation is high year-round. In contrast, evapotranspiration

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Table II. Precipitation trends for three closest stations to our Wageningen station. Distances between Wageningen and the three stations are indicated.

Interval Season	1928–2008 Wageningen (% decade^{-1})	1901–2001 De Bilt (35 km) (% decade^{-1})	1901–2001 Heerde (55 km) (% decade^{-1})	1901–2001 Winterswijk (75 km) (% decade^{-1})
Year	$+0.8 \pm 1.6$	$+1.6 \pm 1.0$	$+1.4 \pm 0.8$	$+0.9 \pm 0.8$
Winter	$+1.6 \pm 3.0$	$+3.1 \pm 1.2$	$+2.3 \pm 1.1$	$+1.2 \pm 1.1$
Summer	-1.0 ± 3.9	$+0.6 \pm 1.2$	$+0.5 \pm 1.1$	$+0.6 \pm 1.0$

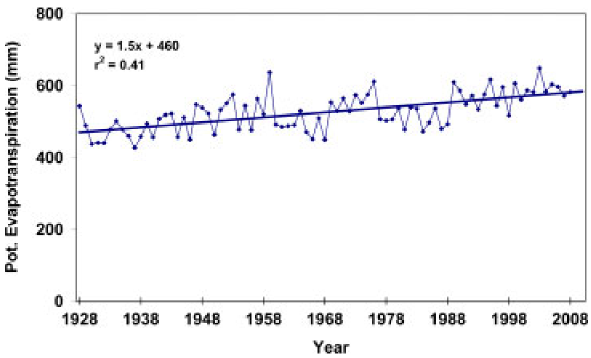

Figure 4. The courses of Makkink's seasonal potential evapotranspiration, their trends and correlation coefficients during the observation period. Winter, 1 December–1 March; Spring, 1 March–1 June; Summer, 1 June–1 September; Fall, 1 September–1 December. This figure is available in colour online at www.interscience.wiley.com/ijoc

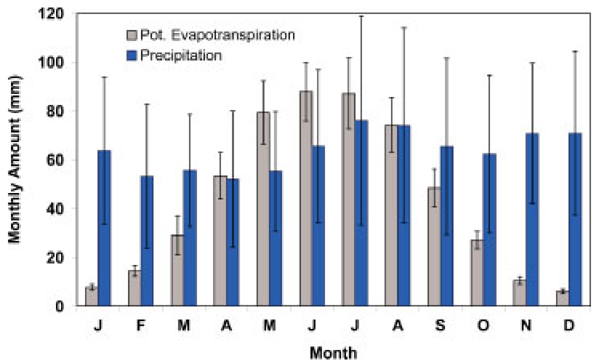

Figure 5. Monthly distributions of potential evapotranspiration and precipitation and their standard deviations during the observation period. This figure is available in colour online at www.interscience.wiley.com/ijoc

Table III. The statistical significance results in the trends of the 10-yearly potential evapotranspiration.

Season	Mean (mm)	Absolute trend (mm decade^{-1})	% decade^{-1}	Significance ($\alpha = 0.05$)
Year	525	$+13.93 \pm 3.78$	+2.7	Yes
Winter	30	$+0.57 \pm 0.25$	+1.9	Yes
Spring	160	$+5.85 \pm 1.69$	+3.7	Yes
Summer	250	$+6.18 \pm 9.84$	+2.5	No
Fall	85	$+1.39 \pm 0.86$	+0.6	Yes

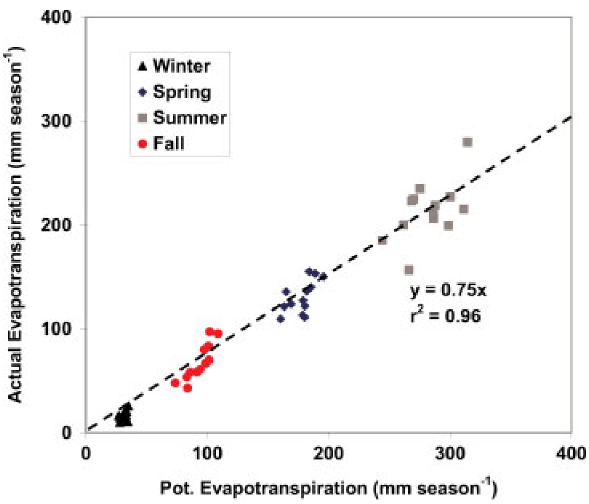

Figure 6. Scattergram of seasonal actual evapotranspiration *versus* seasonal potential evapotranspiration between 1994 and 2008. The unbiased linear regression line is indicated. Winter, 1 December–1 March; Spring, 1 March–1 June; Summer, 1 June–1 September; Fall, 1 September–1 December. This figure is available in colour online at www.interscience.wiley.com/ijoc

shows an annual cycle comparable with the annual cycle found for global radiation (Jacobs *et al.*, 2009).

It is interesting to analyse the relation between potential evapotranspiration and actual evapotranspiration as observed with the EC technique, using the available data from 1992 to 2008 (Figure 6, unbiased linear regression also depicted). On average, the seasonal actual evapotranspiration is 75% of the potential evaporation with a relatively high correlation coefficient of $r^2 = 0.96$. The results of the spring and fall seasons lie best on the regression curve because during these seasons, the actual evapotranspiration is hardly affected by soil moisture shortage. During the summer season, however, soil moisture shortage can considerably affect the actual evapotranspiration, which is clearly demonstrated by the higher deviation of the summer results in Figure 6. In Figure 6, the winter season results lie below the linear regression line. Possible reasons for this systematic deviation are that the winter EC results are less reliable due to the low fluxes but also due to the long period of wet windows of the H_2O gas analyser (Heusinkveld *et al.*, 2008).

We originally anticipated a higher ratio between actual and potential evapotranspiration. For example, in the literature, this ratio is nearly one for well-watered or irrigated crops. Garatuza-Payan *et al.* (1998) had a ratio

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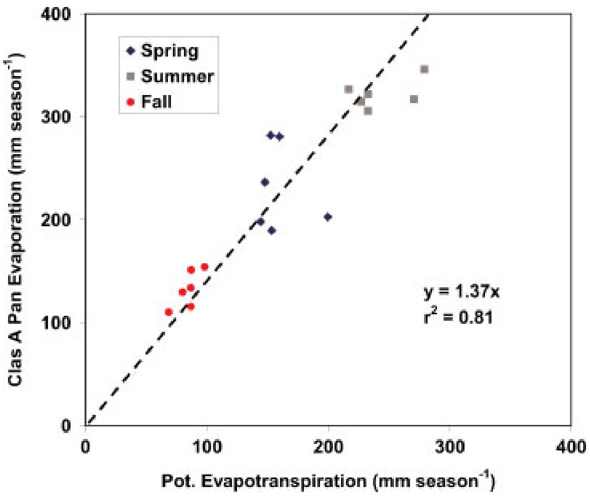

Figure 7. Scattergram of seasonal class A pan evaporation *versus* seasonal potential evapotranspiration between 1984 and 1989. The linear regression line is indicated. Spring, 1 March–1 June; Summer, 1 June–1 September; Fall, 1 September–1 December. This figure is available in colour online at www.interscience.wiley.com/ijoc

close to 1.0 for various well-irrigated crops and Jacobs and De Bruin (1998) had a ratio of 0.94 for a maize canopy for a wet summer season. In the present study, however, dry spells in all seasons can occur where the actual evapotranspiration is affected by a water shortage. This is probably the reason for the lower ratio between actual and potential evapotranspiration found in the present study.

In Figure 7, the actual evapotranspiration is well correlated to Makkink's potential evapotranspiration, E_{pot} for a mid-latitude grass region. This means that, in a simple way, monthly and seasonal estimates of actual evapotranspiration, E_{act}, can be made by measuring the global radiation and the air temperature in combination with a crop coefficient ($E_{act} = 0.75E_{pot}$). It is known that in the wet tropics, there is a high correlation between Makkink's potential evapotranspiration and actual evapotranspiration as well (De Bruin, 1987). As a consequence, it must be expected that in the wet tropics, estimates of actual evapotranspiration can also be made with this technique.

The class A pan evaporation is an estimate for open water evaporation and is best comparable with potential evaporation. Data were available for the class A pan evaporation but only for six consecutive years. The seasonal potential evapotranspiration *versus* the seasonal class A pan evaporation is plotted in the scattergram of Figure 7 along with the unbiased linear regression line. On average, the seasonal class A pan evaporation is 137% of the potential evapotranspiration with a relatively high correlation coefficient of $r^2 = 0.81$. Thus, the class A pan evaporation is considerably higher than the potential evapotranspiration. The main reason for this characteristic is that at most times during the night, the water temperature of the pan is higher than the surrounding air temperature, which causes continuous pan evaporation (Jacobs *et al.*, 1998). This nighttime evaporation period, however, depends heavily on the daytime irradiation load and on nighttime radiative and convective cooling. For a mid-latitude region, a relatively higher scattering for pan evaporation must be expected than for actual evapotranspiration. This high-scattering effect in the pan evaporation can easily be inferred from Figures 6 and 7.

4. Conclusions

Precipitation measurements and potential evapotranspiration estimates were made during a period of 80 years at the meteorological observatory of Wageningen University. For 15 consecutive years, the actual evapotranspiration was measured by the EC technique and for 6 consecutive years, the class A pan evaporation was measured. After analysing the data series, the conclusions are summarised as follows:

1. The mean precipitation amount was (765 ± 130 mm annum^{-1} with a high interannual variability of CV = 17.0%.
2. The precipitation shows a mean increase of 6 mm decade^{-1} (0.8% decade^{-1}) during the observation period. This increase is relatively small and lies within the interannual variance. Moreover, a statistical significance test shows that this trend was not significant ($\alpha = 5\%$).
3. The small precipitation increase mainly occurs during the winter season with 3 mm decade^{-1} (1.6% decade^{-1}). The summer season, however, shows a small decrease of about 2 mm decade^{-1} (−1.0% decade^{-1}). For all seasonal trends, however, the statistical significance tests show that these trends were not significant ($\alpha = 5\%$).
4. The mean potential evapotranspiration amounts was 525 ± 50 mm annum^{-1} with an interannual variability of CV = 9.5%, which is relatively low and is much smaller than the interannual variability of the precipitation.
5. The potential evapotranspiration shows a mean increase of 14 mm decade^{-1} (2.7% per decade) during the observation period. This increase lies within two times the interannual variance. A statistical significance test showed that this trend was significant ($\alpha = 5\%$).
6. The potential evapotranspiration shows a clear seasonal pattern with a relatively small seasonal variance, whereas the precipitation is more or less evenly distributed over the year with a relatively high seasonal variance. For all seasonal trends, the statistical significance tests showed that these trends are significant ($\alpha = 5\%$) except for the summer season.
7. For both a mid-latitude and a wet tropic region, the seasonal actual evapotranspiration is well correlated with Makkink's seasonal potential evapotranspiration ($E_{act} = 0.75E_{pot}$), with a high correlation coefficient of $r^2 = 0.96$. This means that the actual evapotranspiration can be estimated by measuring only the global radiation and air temperature in combination with a crop coefficient.

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8. For a mid-latitude region, Makkink's seasonal potential evapotranspiration is less well correlated to the seasonal class A pan evaporation ($E_{\mathrm{pot}} = 0.73E_{\mathrm{pan}}$) with a relatively lower correlation coefficient of $r^2 = 0.85$.

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