THE DEPENDENCE OF DAILY PRECIPITATION ON TEMPERATURE

A.M.G. Klein Tank and G.P. Können
Royal Netherlands Meteorological Institute KNMI
P.O. Box 201, 3730 AE De Bilt, The Netherlands

1 Introduction

Climate change impact studies require scenarios for elements like precipitation, temperature and solar radiation. On the spatial- and time-scale of interest to these studies, General Circulation Models (GCMs) frequently fail to reproduce many of the statistical characteristics of such climate elements. In the literature, several downscaling techniques are proposed to retrieve the required information (Giorgi et al., 1990; Zorita et al., 1992). But their results remain sensitive to the quality of the GCM background-fields. Another approach is to adjust the parameters of a stochastic weather generator in order to generate synthetic time series with the statistical characteristics of a possible future climate (Wilks, 1992). In many cases however, it proves to be difficult to preserve meteorological consistency between the different elements of a climate change scenario.

In this perspective, we studied the relation on rain days between local daily precipitation amounts and temperature. This relation was described earlier in Können (1983) and Klein Tank and Buishand (1993). The latter authors show that, in a statistical model representation, the relation can be used to transform time series of observed daily precipitation amounts and temperature into internal consistent daily time series that may occur in a future climate. In the present paper we explore an objective method to separate the amounts due to ground-driven convection from those due to fronts and other large-scale systems. This separation can be used to determine the appropriate functions in the statistical model. Besides that, the study of the temperature dependence of both precipitation forming mechanisms may serve a physical-climatological description of precipitation at different locations and different climates.

2 Precipitation - temperature relations

Figure 1 presents the empirical relation for rain days (precipitation≥0.1 mm) between mean precipitation amount R and daily mean surface air temperature T at De Bilt (the Netherlands). Apart from the two outliers at very low temperatures caused by two rare long-lasting snow events, three regimes can be distinguished. In the first one, at the left hand side of the figure, the mean amount increases with temperature. In the second (intermediate temperature) regime precipitation decreases with temperature. The third regime consists of a steep rise in mean amount at high temperatures.

The increase of the moisture content with temperature in a saturated atmospheric column (Clausius Clapeyron) causes fronts and other weather systems to produce more rain at higher temperatures. This effect determines the shape of the graph in the first regime of Figure 1. The behaviour in the second regime, where mean amounts decrease, is due to a decreasing activity of these systems in the meteorological situations belonging to that temperature range. Figure 2 shows the mean precipitation intensity (here defined as the mean amount per wet hour) as a function of the daily mean surface air temperature. In this figure the first and second regime are indistinguishable. Apparently, the decreasing activity in the second regime of Figure 1 is caused by a decreasing mean number of rain hours rather than by a decreasing rain intensity.

At higher temperatures ground-driven convection becomes important as a precipitation forming mechanism. Since the surface air temperature reaches its maximum in the afternoon, the mean amount produced by this mechanism should also show a maximum in this part of the day. Rain produced by large-scale weather systems on the other hand, should not show this behaviour because these systems have no preferential time for arriving or formation. In Figure 3 the mean precipitation amount at every hour of a rain day is shown for rain days with $T \leq 17$°C and rain days with $T > 17$°C. In the high temperature class, there is a distinct diurnal variation, with a minimum in the morning and a maximum in the afternoon, whereas in the low temperature class diurnal variation is absent.

On the basis of Figure 3, an objective classification is made into precipitation amounts due to fronts and other large-scale systems and precipitation amounts due to ground-driven convection. The mean excess in the afternoon (12-24 UT) over the morning (0-12 UT) is defined here as convective precipitation, whereas twice the mean morning amount is defined as rain from large-scale weather systems, called here frontal rain. Figure 4 shows the temperature dependence of the mean frontal and convective amounts defined this way. It is seen that convective precipitation is limited to temperatures above 15°C. Furthermore convective precipitation is dominating in the third regime where there is a steep increase in both mean precipitation amount per wet day and in intensity (Figures 1,2).

3 Discussion

The objective classification of daily precipitiation in mean frontal and convective amounts will not always match with that of routine weather codes. It will for instance classify the amounts from showers in winter troughs as frontal rain, since these amounts are hardly affected by the diurnal cycle in surface air temperature. On the other hand, the increasing amounts of synoptic fronts in the afternoon due to the relatively high surface air temperature, will be classified as convective. It turns out that about one third of the total amount classified here as frontal rain, originates from convective precipitation according to the weather codes.

According to the objective classification ground-driven convection is the dominating precipitation forming mechanism in the third regime. For this mechanism, the temperature dependence of the precipitation intensity I can be obtained from scaling rules (van Ulden, 1993). When the relation between the saturated vapour pressure e_s and temperature is approximated by

$$e_s \approx 6.11 \exp[17.57\,T/(241.8+T)] \approx 6.11 \exp[0.073\,T] \qquad (hPa) \qquad (1)$$

(Magnus approximation) it follows that I for convective precipitation also depends exponentially on temperature but now with a coefficient 1.5 times that in equation (1). This statement is equivalent to the statement that the square of the vertical velocity at cloudbase is proportional to equation (1). It is difficult to verify this theory with Figure 2, since there are only few observations in the third regime. When the maximum temperature T_{max} is considered instead of mean temperature, there are more observations. Besides that T_{max} is a better indicator of ground-driven convection than the daily mean temperature. For T_{max}>19°C a coefficient of 0.10 is found (95% confidence interval: 0.08 to 0.11) whereas for T_{max}>21°C the coefficient is 0.11 (95% confidence interval: 0.08 to 0.13). These values are close to the expected value of $1.5 \cdot 0.073 = 0.110$. The relation described here can be applied to the mean daily convective amounts as well.

The seasonal dependence of the precipitation - temperature relation in Figure 1 is significant at the 5% level (Klein Tank and Buishand, 1993). It seems that this is mainly due to seasonal differences in the temperature range of the second regime, where mean frontal amounts decrease. In the Netherlands, the temperatures of this regime occur only in the spring, the summer and the autumn. Compared to the summer, the second regime in the spring is shifted about 5°C towards lower T, while in the autumn it lies in between. The reason for this seasonal variation may well be the differences in meteorological situations that cause rain days at a given temperature. A relatively large number of high pressure situations on rain days in the spring will cause a de-activation of fronts at lower temperatures and, accordingly, a downward shift of the second regime. This agrees with the observed mean surface air pressure at De Bilt, which increases faster with temperature between 13°C and 17°C in spring than in summer.

The present paper deals mainly with the relation between precipitation and daily mean surface air temperature T. When maximum temperature T_{max} is chosen, this mainly affects the behaviour of the mean convective amounts. The increasing diurnal cycle in surface air temperature with increasing mean temperature causes that the range where frontal and convective precipitation in Figure 4 overlap becomes somewhat smaller. Convective precipitation is then limited to T_{max}>19°C. This leads to a more pronounced relative minimum in Figure 1. Besides that, the rise in the third regime is less steep when maximum temperature is considered instead of daily mean temperature. The choice of T or T_{max} depends on the application that is foreseen.

4 Applications

On the basis of the precipitation-temperature relation, time series of observed daily precipitation amounts and temperature can be transformed into series that may occur in a future climate. Klein Tank and Buishand (1993) use a statistical model for the observed relation between precipitation and temperature (Figure 1). From this they derive a temperature dependent factor that gives the relative change in mean daily precipitation due to a certain temperature perturbation. Since the coefficient of variation of the daily precipitation amounts (the standard deviation divided by the mean) hardly changes with temperature, the obtained factor can be applied to all individual rain days in the record. This method assumes implicitely that the precipitation - temperature relation is preserved in a changing climate, in which case the transformation conserves the internal consistency in the series. At the moment the method is applied in hydrological and crop growth studies in the Netherlands. Applying it to the time series of De Bilt and assuming a systematic temperature change of +3°C and no change in the number and sequence of rain days results in an increase in annual mean rainfall of 9% from 780 to 850 mm (+20% in winter and +4% in summer).

To support the assumption that the relation between precipitation and temperature is in first approximation preserved in a changing climate, it is important to study in more detail which parts of Figures 1 and 4 are most sensitive to spatial and seasonal variation, and which parts are relatively constant. Our first impression is that, as long as orographic effects are small, the second regime (drop of large-scale frontal rain) is most sensitive to location and season whereas the first (increasing frontal activity) and third regime (ground-driven convection) behave rather similar in different climate zones and seasons.

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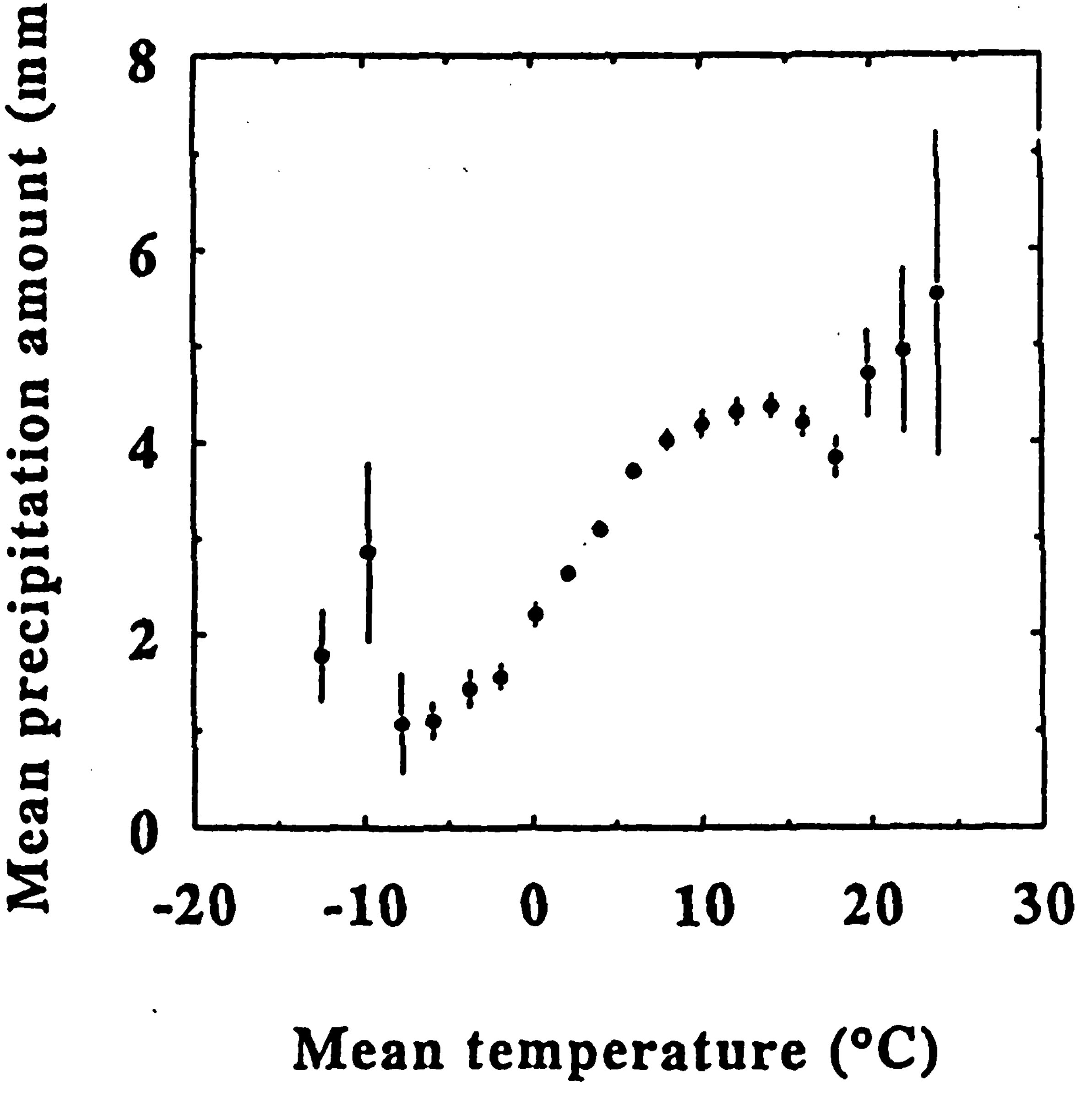

Figure 1 Mean precipitation amount as a function of daily mean surface air temperature on rain days at De Bilt (1906-1990). The error bars indicate the standard deviations of the means in the temperature intervals of 2°C. At the extreme temperatures there are only a few rain days in such an interval (about 10) compared to the intermediate temperatures (about 1500). 57% of the total number of days is a rain day (≥0.1 mm).

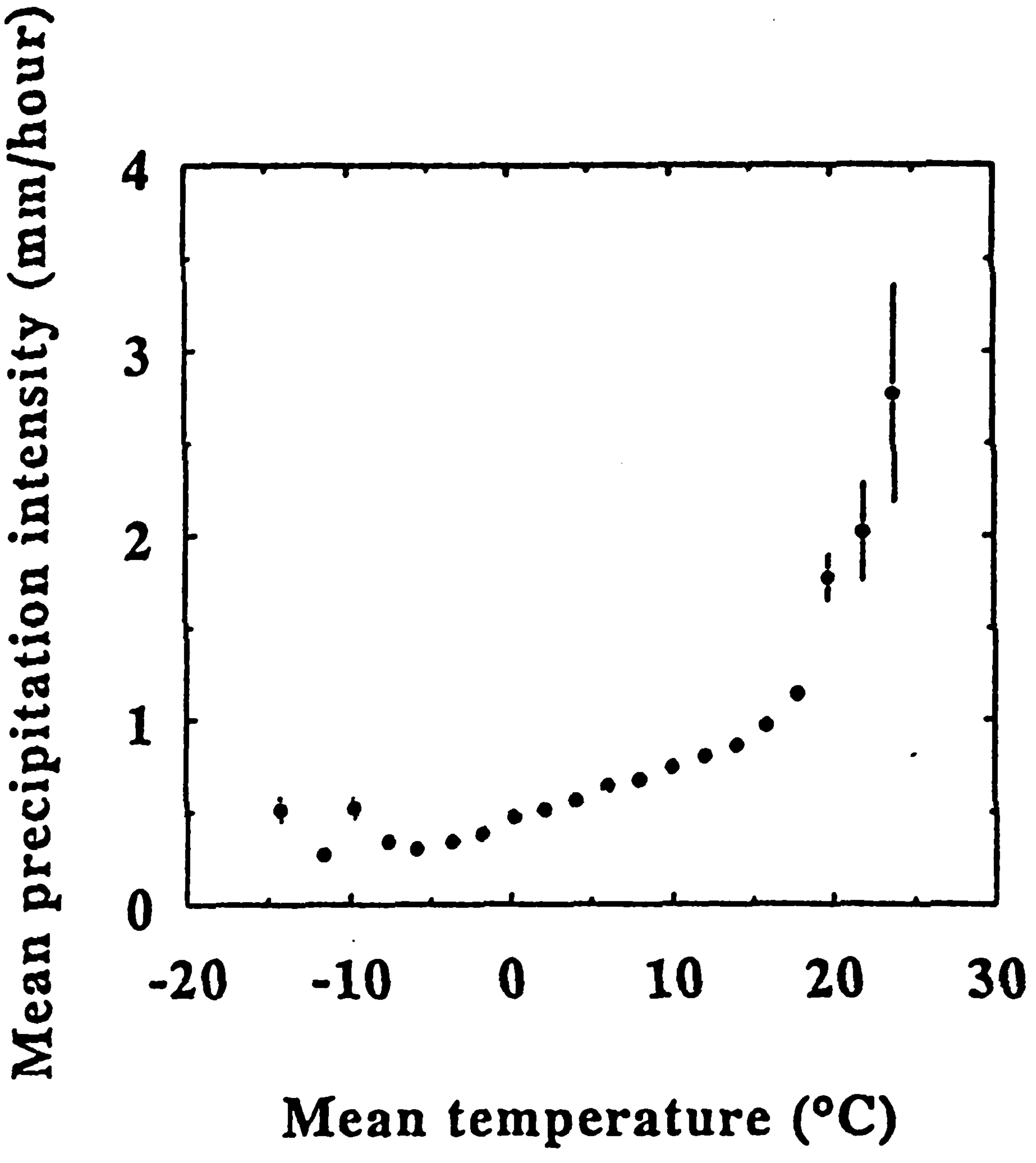

Figure 2 As Figure 1 but now the mean precipitation intensity (mean amount per wet hour) is shown as a function of daily mean surface air temperature on rain days.

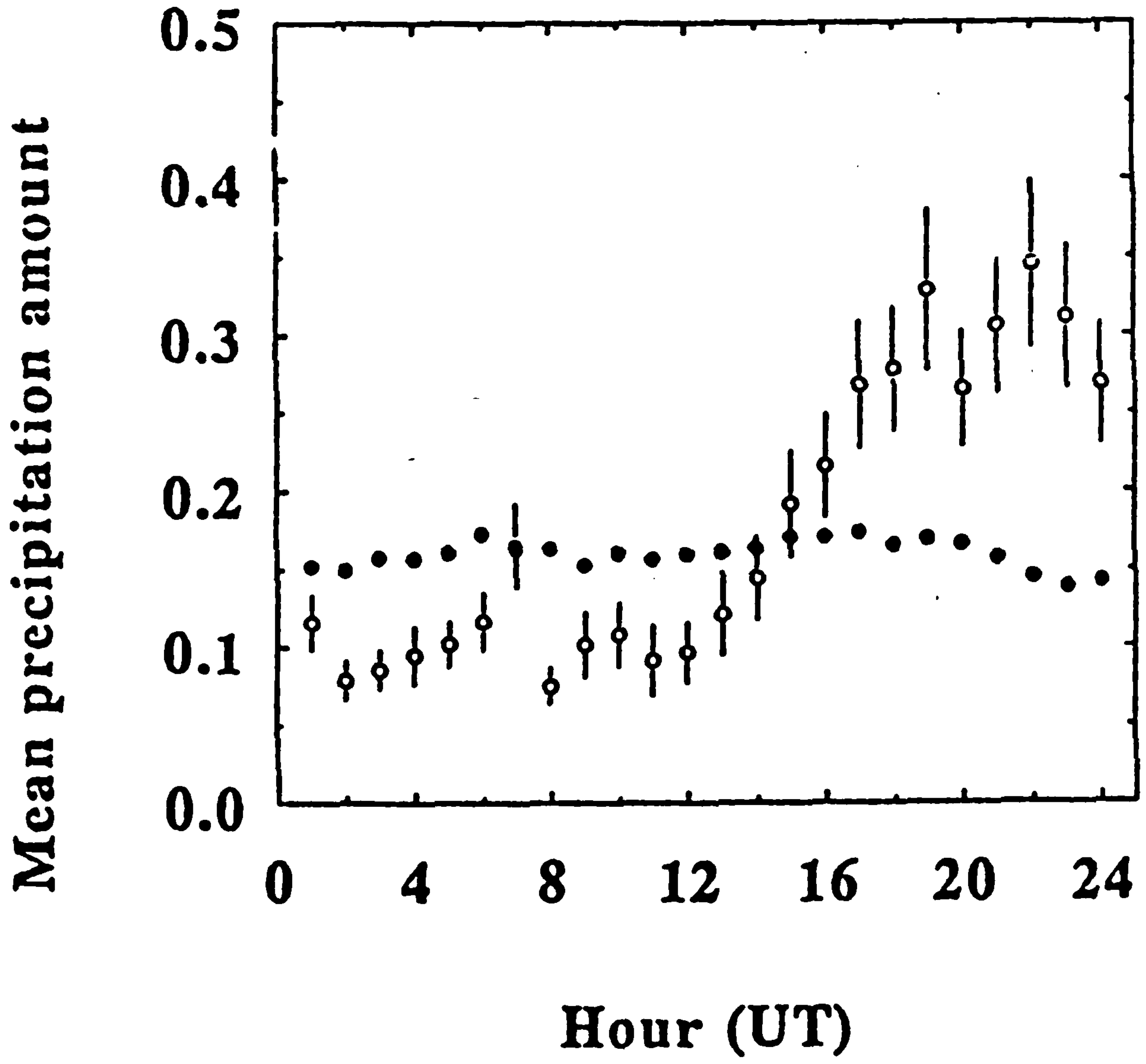

Figure 3 Mean precipitation amount at every hour of a rain day at De Bilt (1906-1990) for two temperature intervals: $T \leq 17$°C (solid circles) and $T > 17$°C (open circles). The error bars indicate the standard deviations of the means; for $T \leq 17$°C these error bars are to small to portray.

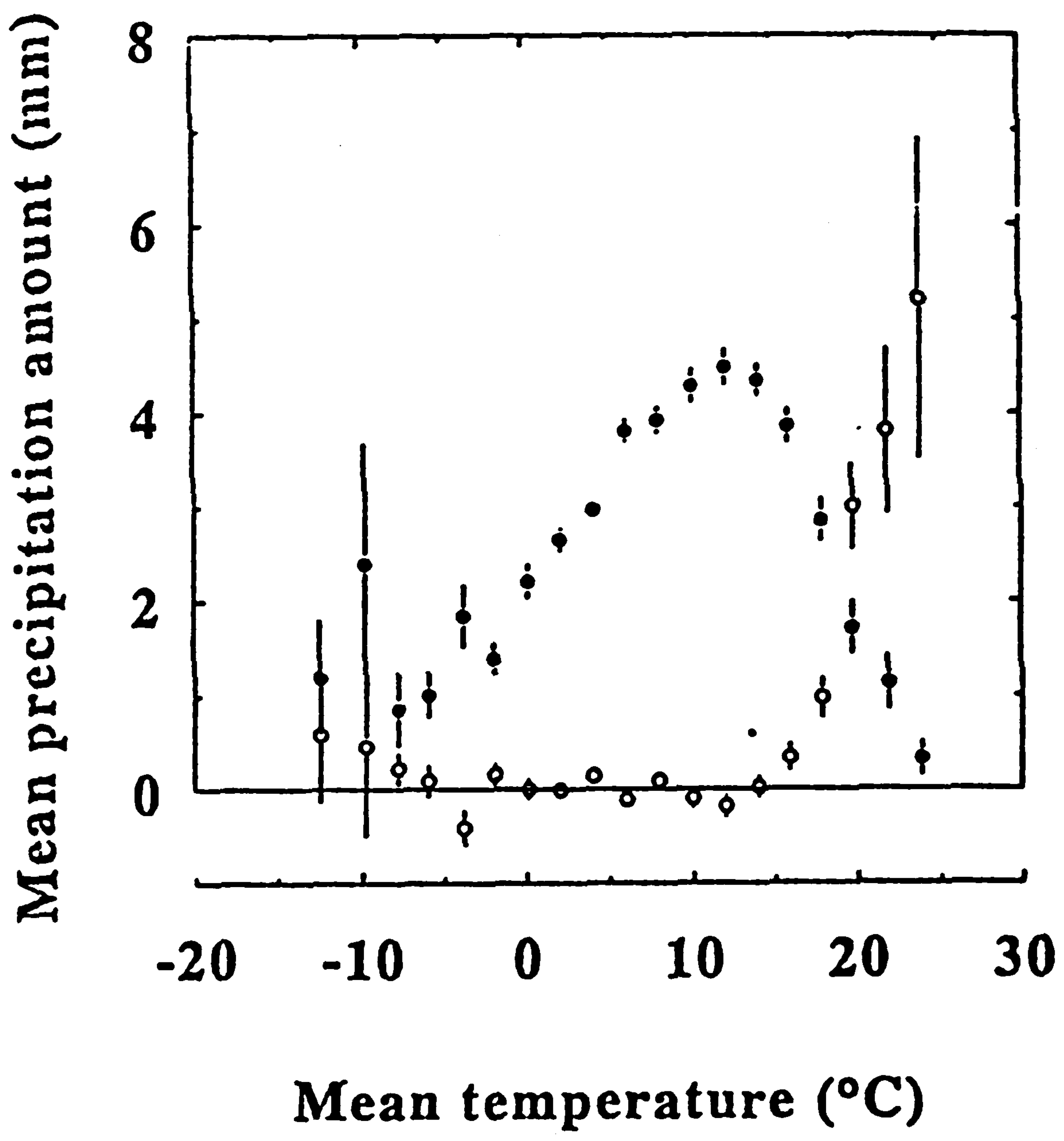

Figure 4 As Figure 1 but now the mean amounts are split objectively into frontal amounts (solid circles) and convective amounts (open circles).