Hydrol. Earth Syst. Sci. Discuss., 8, 4701–4719, 2011
www.hydrol-earth-syst-sci-discuss.net/8/4701/2011/
doi:10.5194/hessd-8-4701-2011

Hydrology and
Earth System
Sciences
Discussions

# Scaling and trends of hourly precipitation extremes in two different climate zones – Hong Kong and the Netherlands

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Received: 27 April 2011 – Accepted: 27 April 2011 – Published: 11 May 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

Hourly precipitation extremes in very long time series from the Hong Kong Observatory and the Netherlands are investigated. Using the 2 m dew point temperature from 4 h before the rainfall event as a measure of near surface absolute humidity, hourly precipitation extremes closely follow a 14 % per degree dependency – a scaling twice as large as following from the Clausius-Clapeyron relation. However, for dew point temperatures above 23 °C no significant dependency on humidity was found. Strikingly, in spite of the large difference in climate, results are almost identical in Hong Kong and the Netherlands for the dew point temperature range where both observational sets have sufficient data. Trends in hourly precipitation extremes show substantial increases over the last century for both De Bilt (the Netherlands) and Hong Kong. For De Bilt, not only the long term trend, but also variations in hourly precipitation extremes on a inter-decadal timescale of 30 yr and longer, can be linked very well to the above scaling; there is a very close resemblance between variations in dew point temperature and precipitation intensity with an inferred dependency of hourly precipitation extremes of 10 to 14 % per degree. For Hong Kong there is no connection between variations in humidity and those in precipitation intensity in the wet season, May to September, consistent with the found zero-dependency of preciptation intensity on humidity for dew points above 23 °C. Yet, outside the wet season humidity changes do appear to explain the positive trend in hourly precipitation extremes, again following a dependency close to twice the Clausius-Clapeyron relation.

## 1 Introduction

It is generally conceived that the intensity of precipitation extremes will increase as the climate warms (IPCC, 2007). The primary reason for this expectation is the fact that the maximum moisture content of the atmosphere increases with approximately 7 % per degree temperature rise, which follows from the Clausius-Clapeyron relation (hereafter C-C relation). If the relative humidity does not change, then increases in atmospheric humidity (water vapor) occur at the same rate. Indeed, in models it is generally found that increases in near surface humidity follow the C-C relation, in particular over wet surfaces like the ocean, and this can be understood from the surface energy budget (Held and Soden, 2006; Schneider and O'Gorman, 2007; O'Gorman and Muller, 2010; Sherwood et al., 2010). There is also observational support for increasing moisture above the oceans (Santer et al., 2007). Over large continental areas however substantial deviations may occur, mainly due to soil moisture depletion. For instance, O'Gorman and Muller (2010) found a 1–2 $\% \mathrm{K}^{-1}$ lower rate over the continents in a large ensemble of GCM results.

Increases of daily precipitation extremes at the rate predicted by the C-C relation have been found in two early studies with global climate model results (Allen and Ingram, 2002; Pall et al., 2007). However, in several recent studies it has been argued that there is no clear reason why changes in precipitation extremes should follow a C-C scaling exactly. Changes in the atmospheric large scale motions (Emori and Brown, 2005), the moist-adiabatic lapse rate (O'Gorman and Schneider, 2009), the dynamics of the clouds (Trenberth et al., 2003) and limitations in moisture increase due to soil water depletion (Berg et al., 2009) can induce deviations from a C-C scaling.

Accordingly, in two earlier studies we found increases in hourly precipitation extremes of approximately two times the C-C relation from observations of the Netherlands, Belgium and Switzerland for daily mean temperatures above 14 °C. There are several questions open to debate concerning this enhanced temperature dependency compared to the C-C relation – a "super" C-C scaling. These questions concern the cause of the observed relation, the generality of the results, the role of humidity, and the applicability of the observed relation to climate change.

Haerter and Berg (2009) argue that the super C-C scaling results from a dependency of the frequency of occurrence of large-scale versus convective precipitation with temperature. Since convective events are by their nature more intense than large-scale events, and convective events become more frequent with rising temperature, this could statistically induce an enhanced temperature dependency. Our hypothesis is that the super C-C scaling is caused by a feedback from the dynamics of the cloud due to latent heat release (Trenberth et al., 2003; Lenderink and van Meijgaard, 2009).

If the super C-C scaling of hourly extremes is due to statistical effects (for instance, related to the seasonal cycle) it is unlikely that it is a good predictor of changes in hourly precipitation extremes due to climate change. If, on the other hand, it is related to how convective storms react to increasing humidity it could be a good predictor.

Another question is whether (and, if so, at what temperature) there is a limit to the super C-C dependency. There are some indications of such a limit in the results of Lenderink and van Meijgaard (2008, 2010), but the temperature range at which this occurs is not well sampled in the data.

Further, the availability of moisture under warm conditions is an important issue. It has been argued that soil drying, and a resulting decreases in relative humidity at high temperatures, could cause a limit to the super C-C scaling of precipitation extremes (Berg et al., 2009). Indeed, this may explain the lower dependency of hourly precipitation extremes, or even decrease with temperature, found in recent studies for Australia and the United States (Hardwick Jones et al., 2010; Shaw et al., 2011). For this reason, Lenderink and van Meijgaard (2010) introduced the dew point temperature as a direct measure of atmospheric absolute humidity. For the Netherlands temperature and dew point temperature give similar results. This is because the relative humidity is approximately constant over a large temperature range, which implies a practically constant offset between temperature and dew point temperature. However, this is likely not a general result.

For these reasons it is of interest to investigate hourly precipitation extremes from stations from a warmer, more tropical climate zone, where precipitation is more dominated by convective systems and where the higher temperature range is well sampled. Here, we investigate a very long time series from 1885 to 2009 of hourly precipitation measured at the Hong Kong Observatory, and compare results with earlier findings.

The length of the observational data from De Bilt (the Netherlands) and Hong Kong also allows us to look at trends and natural variability in hourly precipitation extremes. It is of particular interest to investigate whether trends in extremes can be explained by temperature and/or humidity changes using the above scaling relations. If this is the case, we can have more confidence that the observed scaling can be used as a predictor of the influence of climate change on hourly precipitation extremes.

## 2 Data and methods

Three data sets are used. First, observations made at the Hong Kong Observatory, located in the urban centre of Hong Kong (hereafter, HKO). Continuous observations of hourly temperature, humidity, and precipitation since 1885 are available, except from 1940 until 1946 during World War II (Lee et al., 2006; Wong et al., 2010). Second, observations at De Bilt in the centre of the Netherlands since 1906 (hereafter, DB). Hourly precipitation is available for the whole period, but before 1950 hourly humidity measurements are lacking. Third, observations of 27 stations within the Netherlands of the last 15 yr from 1995 until 2010 (hereafter, NL). These stations are relatively closely spaced in homogeneous environment – a flat river delta – so that the hourly data of precipitation, humidity, and temperature of separate stations can be pooled together to obtain one large data set containing approximately 400 yr of data (see Supplement of Lenderink and van Meijgaard (2010) for more details).

A scaling of extreme precipitation intensity was first found as a function of temperature (Lenderink and van Meijgaard, 2008). In Lenderink and van Meijgaard (2010) we introduced the dew point temperature, which is the temperature at which the air is fully saturated, as a direct measure of the atmospheric humidity. Here, besides the daily mean temperature, we will use the dew point temperature taken four hours before each hourly precipitation observation. This is considered to be a good measure of the near surface humidity from the air mass in which the shower develops. Taking this measure gave the best scaling behaviour for NL: these data gave the most constant dependency across the largest range in dew point temperatures (see also Supplement of Lenderink and van Meijgaard, 2010). To keep the text concise we will omit "taken four hours before each hourly precipitation observation" in the following, and just use "hourly dew point temperature". We note that dew point temperatures at the time of the rainfall event are already affected by the shower itself. This is apparent from the time series of the dew point temperature, which show in many cases a considerable drop during the shower. The latter is likely due to the transport of drier air from above by the downdrafts associated with the convective cloud.

Dependencies of hourly precipitation intensity on the (dew point) temperature are computed using a binning technique following Lenderink and van Meijgaard (2008, 2010). Binning is done in classes of 2 °C width, and the bins are overlapping with steps of one degree. From the binned data different percentiles are computed from the distribution of wet events. Here, wet events are hours with precipitation amounts larger than or equal 0.1 mm $h^{-1}$(for examples of these distributions see Supplement, Sect. a). In addition to the percentiles computed from the raw data, the 99th and 99.9th percentile are computed also from a Generalized Pareto Distribution (GPD) (Coles, 2001) fit to the upper 4 % of the data. Uncertainty estimates for the 99th and 99.9th percentiles are derived from the error estimates of the GPD fit. The 98 % confidence interval of this fit is indicated by the shading.

Long-term trends are computed from a 15-yr sliding window analysis using data from HKO and DB. For each 15-yr block period, different percentiles are computed from a GPD fit to the upper 10 % of the precipitation observations (conditioned to be wet). The reason to look at the statistics of wet events only is that these are less dependent on variations in the atmospheric circulation (Lenderink et al., 2007), which gives better statistics and enables us to better detect the influence of atmospheric moisture on precipitation extremes. For each month and 15 yr period, the 95th, 99th and 99.5th percentile are first computed from the GPD fit. Anomalies compared to the average of all 15-yr periods are then computed, and then averaged over several months, e.g., June, July and August (JJA) or the months May until October (MJJASO). This measure is denoted as $\Delta Pr_h$. Error bands are based on the 98 % confidence interval of the GPD fit procedure, assuming errors of the separate months to be independent. The choice of 15 yr is a compromise between being able to determine the different extremes (which are very noisy with less than 10 yr of data) and being able to capture inter-decadal variations (which are more damped with longer aggregation periods). Here, we use the daily mean dew point temperature because hourly observations are not available for the De Bilt time series before 1950. We note that for the period 1950–2006 similar results are obtained using hourly dew point temperatures.

## 3 Scaling of hourly precipitation extremes

Figure 1 shows scaling relations of hourly precipitation extremes derived using the daily mean temperature for data from the Hong Kong Observatory (HKO) and the 27 stations in the Netherlands (NL). For NL, this is the reproduction of Fig. 1d in Lenderink and van Meijgaard (2010), yet with one year more data for each station. There is clear hint of a decrease in precipitation intensity for temperatures above 24 °C in NL, but the number of observations with rain above that temperature is very small and consequently the error bands are large. For instance, above 24 °C there is no observation corresponding to the 99.9th percentile, and this percentile is computed from the extrapolation by means of the GPD fit (indicated by the dashed purple line). There is a very clear fall off in intensity above 24 °C in HKO. Since there are many days (about 50 % of days in 1971–2000) with daily mean temperatures above that temperature in HKO, this fall off in intensity is obviously well sampled. Below 24 °C, both data sources show a super C-C scaling. At the same temperature, and for the same percentile, intensities in HKO are generally larger than those in NL by 20–30 %.

Taking the hourly dew point temperature as predictor, a very consistent scaling is obtained in both HKO and NL (Fig. 2). In the dew point temperature range between 12 and 20 °C, the 99th and 99.9th percentiles are almost identical for both data sources. The dependency is close to 14 % per degree, which is two times the C-C relation. Since

NL and HKO are in completely different climate zones, this universality is a striking result.

Results for HKO also clearly show an upper limit for the increase in precipitation intensity with dew point temperature. For dew point temperatures above 23 °C intensities reach a constant level, which is approximately 65 mm h$^{-1}$ for the 99.9th percentile. Figure 3 shows that about 40 % of all hours have a dew point temperature above 23 °C taken over the whole year, and in summer (JJA) this percentage is even 90 %. Thus it is clear that the range above 23 °C is well sampled in the HKO data, and that the levelling off is not due to poor sampling or a consequence of rather anomalous atmospheric conditions.

Figure 3 shows that the highest precipitation extremes do not necessarily occur for the highest dew point temperatures, which one might expect from Fig. 2. For all hours with precipitation amounts exceeding the 99th percentile ($\approx$ 10 mm h$^{-1}$) in NL, the median dew point temperature is approximately 16 °C. The reason for this is that there are many more precipitation events for the lower and intermediate dew points temperature range than for the highest dew point temperatures (see also Supplement, Sect. a).

From Fig. 3 a dependency of precipitation extremes on the dew point temperature can not be inferred. For instance, for summer in NL the difference in intensity between the 90th and 99th percentile is more than a factor two. The difference in the corresponding dew point temperatures is only about 1–2 degrees (see Fig. 3) and this would yield a dependency of the precipitation intensity of more than 50 % per degree. Obviously, this is not correct and the difference between the two percentiles of hourly precipitation cannot be attributed solely to humidity differences; differences in other atmospheric conditions, like the (mesoscale) circulation, vertical instability and wind shear, are all important as well. Thus, by selecting more extreme precipitation events, one also samples those atmospheric conditions that, besides humidity, give rise more intense precipitation.

Yet, we note that the (cumulative) distributions of the dew point temperature from Fig. 3 are qualitatively consistent with the scaling relations in Fig. 2. On the one hand, in HKO almost all extreme events in summer occur with a near surface humidity above 23 °C, where the dependency on moisture is small. Consequently, there is no difference in distribution of humidity for extreme precipitation events with that occurring on all days. On the other hand, most extreme events in NL occur at humidity levels where the dependency on humidity is still strong: 14 % per degree dew point temperature (Fig. 2). Thus for NL one expects that more extreme precipitation events are characterized by on average higher humidity values as shown in Fig. 3.

## 4 Long term trends over the last century

Figure 4 compares long-term variations in the intensity of hourly precipitation extremes with variations in the dew point temperature (multiplied by 14 % per degree). For DB a very good correspondence between the variations in dew point temperature on days with intense precipitation ($\Delta T_d^*$) and variations in extreme precipitation ($\Delta \mathrm{Pr}_h$) is shown for the months May to October (MJJASO). Not only the trend over the century, but also variations on the inter-decadal time-scale are very similar. (Days with heavy precipitation are defined as the days on which a hourly precipitation observation exceeds the 90th percentile of the distribution of precipitation on wet hours. Similarly to $\Delta \mathrm{Pr}_h$, $\Delta T_d^*$ is first computed seperately for the different months and than averaged.) The dependency of $\Delta \mathrm{Pr}_h$ on $\Delta T_d^*$ however appears somewhat smaller, and the best fit is obtained 11 % per degree (Supplement, Sect. b). For the summer months, June, July, and August, the dependency is 13 % per degree, close to two times the C-C relation. Absolute percentiles of the distribution of hourly precipitation – the 99.5th, 99.9th and 99.95th percentiles – and also the seperate percentiles show very similar time variations (Supplement, Sect. c).

For the wet season May to September (MJJAS) in Hong Kong there is no obvious correspondence between $\Delta \mathrm{Pr}_h$ and $\Delta T_d^*$. Both show upward trends, but on an inter-decadal time scale there is clearly no connection. This is consistent with the fact that the mean dew point temperature for these months is close to or above the threshold

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of 23 °C, where Fig. 2 shows no dependency of precipitation extremes on dew point temperature. The reason for the upward trend in $\Delta\mathrm{Pr}_\mathrm{h}$ could be related to the urbanization (Kishtawal et al., 2010; Ginn et al., 2010) or changing large scale conditions, like for instance the apparent change in strength of the summer monsoon (Xu et al., 2006; Ding et al., 2008).

Outside the wet season, we could find a reasonable good correspondence between $\Delta\mathrm{Pr}_\mathrm{h}$ and $\Delta T_\mathrm{d}^*$ for the months, October, and February until April (O-FMA). The signal-to-noise ratio, however, is worse than that for DB. In November and December, the number of wet events is so low (approximately 3 %) that changes in the extremes could not be determined reliably. A regression of $\Delta\mathrm{Pr}_\mathrm{h}$ on $\Delta T_\mathrm{d}^*$ gives a dependency of 13–16 % per degree (Supplement, Sect. b).

Finally, the long term trends in dew point temperature on extreme wet days $\Delta T_\mathrm{d}^*$ and the average dew point temperature $\Delta T_\mathrm{d}$ are very similar, although on the inter-decadal time scale there are differences (Supplement, Sect. d). The long-term trend in $\Delta T_\mathrm{d}$ is approximately equal to the trend in the mean temperature, consistent with the hypothesis of a constant relative humidity as climate changes. Thus the long term temperature trend is accompanied with a similar trend in dew point temperature, which on the longer term is reflected in the dew point temperatures when intense showers occur.

## 5 Summary and discussion

The dependency of hourly precipitation extremes on near surface humidity (as measured by the dew point temperature) is investigated in data from the Hong Kong Observatory, in comparison with data from the Netherlands. A dependency of hourly precipitation extremes of 14 % per degree is obtained for dew point temperature up to 23 °C. It is striking that very similar results are obtained for both the Netherlands and Hong Kong for dew point temperatures between 12 and 22 °C, in spite of the large difference in climate. Dependencies of hourly precipitation extremes on the daily mean temperature are less consistent in HKO and NL. Both show a super C-C scaling for temperatures up to 24 °C, and a rapid decrease for higher temperatures.

For dew point temperature above 23 °C, which mainly occur in the time series from Hong Kong, extreme hourly precipitation does not increase further with (near surface) humidity. The reason for this limit is unclear, but could be related to constraints in the micro-physical processes in the convective cloud. Nevertheless, this shows that the premise that increased temperatures (and resulting humidity) lead to increases in precipitation extremes is not necessarily true for the (sub)tropics; at least on a hourly time scale our results do not provide evidence for such an increase with temperature.

Long-term variations on an inter-decadal to centennial time scale in hourly precipitation extremes are consistent with the above scaling. For the De Bilt (the Netherlands), long-term variations in precipitation extremes in the summer halve year can be well explained by changes in surface dew point temperatures following a dependency of 10–14 % per degree. For Hong Kong, a correspondence between precipitation extremes and dew point temperature could not be established for the wet season May to September, consistent with the finding of a zero-dependency of the precipitation intensity for high dew point temperatures. The reason for the observed increase therefore remains unclear, but could be related to urbanization or changes in the strength of the summer monsoon. For data from October, and February until April, trends in precipitation extremes could be explained reasonably well by moisture changes, again with a dependency close to 14 % per degree.

Finally, we emphasize that the different analyses and the different data sources, all reveal similar dependencies of hourly precipitation extremes on near surface humidity. We note that there is also limited support for a super C-C scaling from modelling results (Lenderink and van Meijgaard, 2010; Sugiyama et al., 2010). This strengthens our belief that the found large, 10–14 % per degree, dependency of hourly precipitation extremes on humidity is real, and that it may be used as a predictor of the changes in hourly precipitation extremes due to global warming. If the temperature rises 3 degrees – which is the mean of the projected range of 21st century warming according to the

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scenarios issued for the Netherlands (van den Hurk et al., 2007) – the Netherlands may therefore face a 50 % increase of the intensity of hourly precipitation extremes. The impact of such an increase could be substantial, for instance for urban flood management. For Hong Kong, the rising trend of the temperatures is also expected to continue in the 21st century (Lee et al., 2011). This study results suggest that climate change may primarily manifest itself in hourly precipitation extremes occurring in the traditional dry months from October to April.

**Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/8/4701/2011/hessd-8-4701-2011-supplement.pdf.**

*Acknowledgements.* Financial support from the Dutch project Knowledge for Climate (KfC) to KNMI is gratefully acknowledged.

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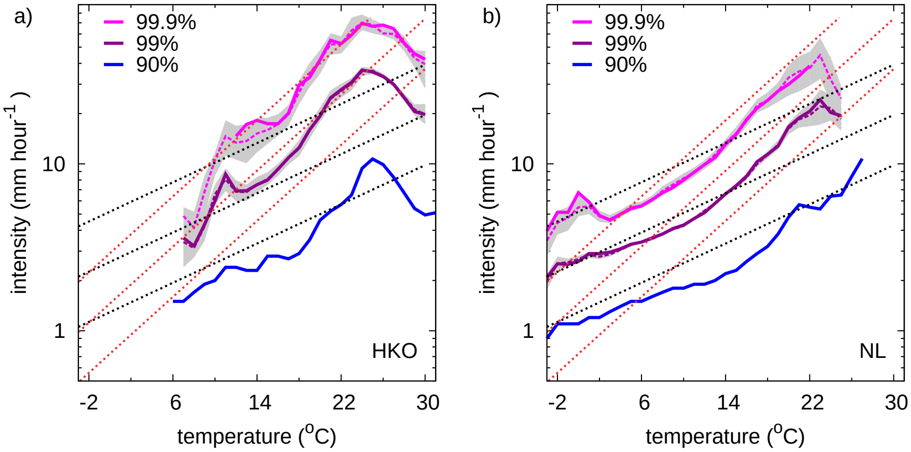

**Fig. 1.** Dependency of different percentiles of hourly precipitation extremes on daily mean temperature (left: HKO; right: NL). Stippled lines are estimates from the GPD fitting procedure, whereas solid lines are the percentiles computed from the raw data (in most cases these overlap). The grey shading denotes the 98 % uncertainty range derived from the GPD fit. Red (black) stippled lines denote dependencies of 14 % (7 %) per degree. For comparison, these lines are identical in all plots; the distance between two lines is a factor 2 in intensity.

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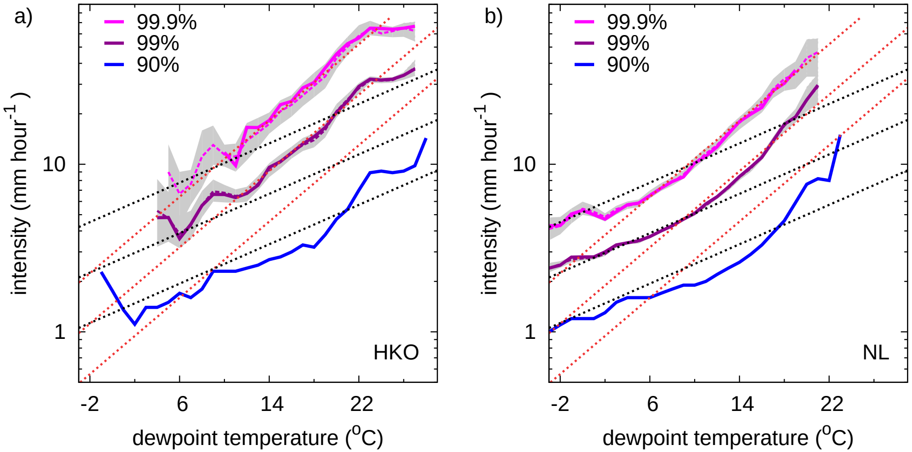

**Fig. 2.** Dependency of different percentiles of hourly precipitation extremes on dew point temperature taken 4 h before each precipitation event (left: HKO; right: NL). Lines and symbols are the same as in Fig. 1.

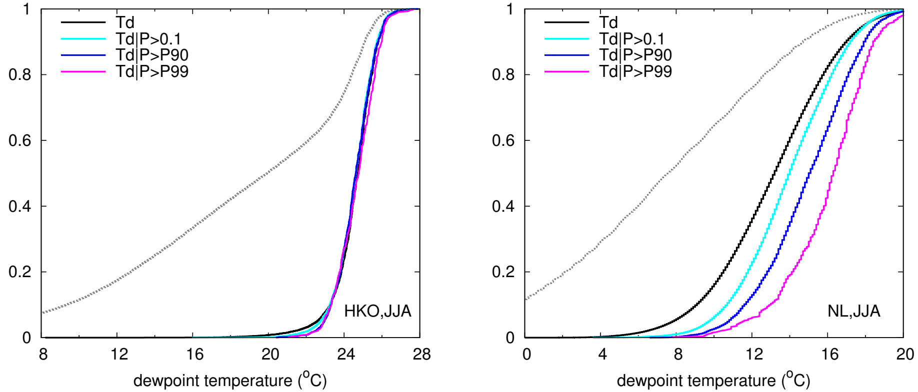

**Fig. 3.** Cumulative density function (CDF) of the dew point temperature for summer (JJA). Distributions of the dew point temperature are plotted for all hours, for hours with precipitation, and for hours with precipitation exceeding the 90th and 99th percentile of hourly precipitation. As in Fig. 2 dew point temperatures are taken 4 h before the precipitation event. The grey stippled line gives the CDF of all hours for the whole year.

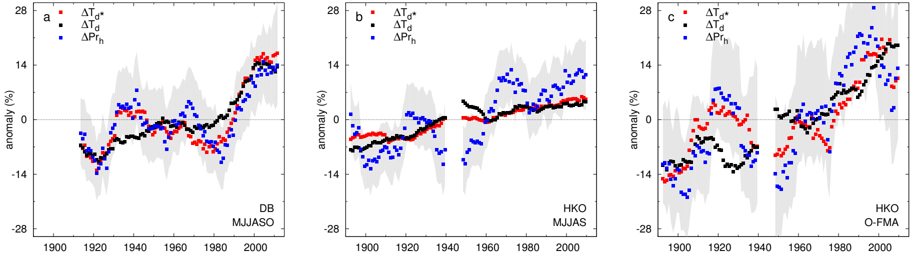

**Fig. 4.** Variations in hourly precipitation extremes ($\Delta Pr_h$, that is, average over 95th, 99th, 99.5th percentiles) (blue dots)) compared to changes in dew point temperature for heavy precipitation days (with hourly precipitation exceeding the 90th percentile) (red dots) and all days (black dots). Anomalies in dew point temperature are multiplied by 14 % per degree in order to compare the time variations in dew point temperature with those in precipitation intensity. Grey bands are 98 % error estimates of $\Delta Pr_h$.