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Discussions

Effects of record length and resolution on the derived distribution of annual precipitation

C. I. Meier[1], J. S. Moraga[2], G. Pranzini[2], and P. Molnar[3]

[1]Department of Civil Engineering, University of Memphis, Memphis, TN, USA
[2]Departamento de Ingeniería Civil, Universidad de Concepción, Concepción, Región del Bío Bío, Chile
[3]Institute of Enviromental Engineering, ETH Zurich, Zurich, Switzerland

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Correspondence to: C. I. Meier (cimeier@memphis.edu), P. Molnar (molnar@ifu.baug.ethz.ch)

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Abstract

Traditional frequency analysis of annual precipitation requires the fitting of a probability model to yearly precipitation totals. There are three potential problems with this approach: a long record (at least 25 ~ 30 years) is required in order to fit the model, years with missing data cannot be used, and the data need to be homogeneous. To overcome these limitations, we test an alternative methodology proposed by Eagleson (1978), based on the derived distribution approach (DDA). This allows for better estimation of the probability density function (pdf) of annual rainfall without requiring long records, provided that high-resolution precipitation data are available to derive external storm properties. The DDA combines marginal pdfs for storm depth and inter-arrival time to arrive at an analytical formulation of the distribution of annual precipitation under the assumption of independence between events. We tested the DDA at two temperate locations in different climates (Concepción, Chile, and Lugano, Switzerland), quantifying the effects of record length. Our results show that, as compared to the fitting of a normal or log-normal distribution, the DDA significantly reduces the uncertainty in annual precipitation estimates (especially interannual variability) when only short records are available. The DDA also reduces the bias in annual precipitation quantiles with high return periods. We also show that using precipitation data aggregated every 24 h, as commonly available at most weather stations, introduces a noticeable bias in the DDA. Our results point to the tangible benefits of installing high-resolution (hourly or less) precipitation gauges at previously ungauged locations. We show that the DDA, in combination with high resolution gauging, provides more accurate and less uncertain estimates of long-term precipitation statistics such as interannual variability and quantiles of annual precipitation with high return periods even for records as short as 5 years.

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1 Introduction

Total annual precipitation and its variability between years are important climatic variables for water balance studies, developing regional climatologies, planning and management of water resources, and assessing water stress in general. Interannual variability in precipitation results from many factors of which long term multi-year atmospheric anomalies, such as ENSO, NAO, etc. (e.g., Higgins et al., 1999; Barlow et al., 2001), the strength and persistence of seasonality (e.g., Fatichi et al., 2012), and stochasticity in weather and precipitation formation in general are key. Interannual variability in precipitation is an important descriptor of the climatic environment and directly impacts the occurrence of droughts (e.g., Dai et al., 2004; Dai, 2011), vegetation productivity in water-limited ecosystems (e.g., Knapp and Smith, 2001; Reyer et al., 2013; Fatichi and Ivanov, 2014), as well as the distribution of rainfall extremes (e.g., Groisman et al., 2005).

A traditional statistical analysis of annual precipitation consists of estimating key statistics (mean, variance, skewness, etc.) and fitting a probability distribution model to the annual (or seasonal) data. In temperate zones, this could be for example a normal or log-normal distribution (e.g., Markovic, 1965; Linsley et al., 1982), fitted to a sample of at least 25 ~ 30 years of data. This approach is often impractical, because at many locations only a few years of precipitation data are available and many records are incomplete. With short records, the estimated statistics and parameters of the fitted probability model are highly uncertain. Moreover, natural fluctuations in climate over decadal or longer time scales, now accentuated by anthropogenic change, imply that most long climate records are not statistically homogeneous and stationary (Milly et al., 2008). This leads to the problem that while long records are required to accurately estimate the statistics and probability distribution of annual rainfall, precipitation itself in fact may be non-stationary over such long periods. Thus, a methodology is needed that would allow for a better estimation of the probability distribution of annual precipitation without requiring long records.

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Eagleson (1978) developed such a methodology by deriving the distribution of annual precipitation from the individual storms making up the yearly totals. Given independent storm arrivals and taking typical models for the marginal probability distributions of storm interarrival times and storm depths, the probability density function (pdf) of annual precipitation can be derived (Eagleson, 1978). Under this derived distribution approach (DDA) only a few years of high resolution precipitation data, from which storm arrivals, depths and durations can be extracted and their distributions estimated, are necessary to arrive at an accurate estimate of the probability distribution of annual precipitation for a site.

The main aim of this paper is to investigate the DDA at two temperate locations in different climates (Concepción, Chile, and Lugano, Switzerland) and to compare it with the traditional procedure of fitting a normal or log-normal distribution to a series of annual precipitation depths. This paper addresses two questions in detail: (a) what is the effect of record length on the estimates of annual precipitation (mean, variance and quantiles) obtained with both methods? (b) What is the effect of temporal resolution (sampling time) on the results? The latter question is important for sites where only daily rainfall data are available, so that the accuracy of storm statistics for the DDA is reduced.

2 Methods

2.1 Study sites and data

The DDA and normal/log-normal probability distributions were fitted to precipitation data for two temperate locations with dissimilar climate. For the first site in Concepción, Chile, the data consists of 19 years of daily and 6 years of weekly pluviograms (paper rain charts) continuously recorded over the period 1975–1999, with a Lambrecht float-recording and siphoning rain gauge. For the second site in Lugano, Switzerland, there is a 32 year-long precipitation record (1981–2012) available from MeteoSwiss (Swiss

Federal Office of Meteorology and Climatology). These are 10 min precipitation depths measured by a Lambrecht tipping-bucket instrument with 0.1 mm resolution. The Swiss data are of very good quality and have recently been used in other studies of storm properties in Switzerland (e.g., Gaál et al., 2014; Molnar et al., 2015).

2.2 Event definition

Using derived distributions first requires defining independent storms in the record, in order to obtain the parameters needed for the marginal distributions of storm depth and interarrival time. Although there are many different approaches for selecting a criterion of event independence (e.g., Dunkerley, 2008), we chose to discriminate successive independent storms based on a Minimum Inter-event Time, MIT (Restrepo-Posada and Eagleson, 1982; Driscoll et al., 1989; Gaál et al., 2014). With this approach, any dry spell between recorded precipitation longer than the MIT defines two independent storms. Conversely, if a gap without precipitation is shorter than the MIT, then we assign both precipitation pulses to the same storm event (see Fig. 1).

For each independent storm, we obtained the following external storm properties from the data: storm depth H, rainfall event duration T_r, time elapsed between the end of the storm and the beginning of the next storm T_b, and time between the beginning of successive storms T_a (interarrival time). These variables are shown in Fig. 1, where storms are simplified into rectangular pulses.

2.3 Derived distribution of annual precipitation

Eagleson (1978) defined annual precipitation (P_a) as the sum of precipitation depths over the finite number of events that occur throughout a year (or wet season). It can thus be considered a compound variable which depends on the number ν of storm events in a given year (wet season), as well as on the storm depths H_j contributed by

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each storm:

$$P_a(\nu) = \sum_{j=1}^{\nu} h_j. \tag{1}$$

Both ν and H_j, are random variables with probability distributions that can be estimated on the basis of available, high resolution precipitation data. We are interested in obtaining the probabilistic behaviour of the compound variable P_a, knowing the pdfs of the storm properties.

In his work, Eagleson (1978) assumed that both the interarrival time T_a and the rainfall depth per storm H_j are identically and independently distributed (iid) variables. The first assumption means that the probabilistic behaviour of these variables is time-invariant, i.e., storms behave similarly in terms of their frequency and rainfall depth, every year, and throughout the year. Although weather disturbances are much more frequent and intense in certain seasons in Concepción and Lugano, there are no clear limits between dry and wet seasons (rainfall events occur all year round) so that P_a corresponds to an integration of the precipitation process at the yearly scale. Homogeneity could also be assumed at the seasonal scale if there were evidence for this in the data. The independence assumption implies that the characteristics of a given storm are not affected by previous rainfall events, i.e., subsequent events result from different weather systems. Under these assumptions the distribution of annual rainfall is given by:

$$f_{P_a}(y) = \sum_{\nu=1}^{\infty} f_{P_{a(\nu)}}(y) \cdot P_\theta(\nu), \tag{2}$$

where $f_{P_a}(y)$ is the probability density corresponding to an annual rainfall of exactly y mm; $f_{P_{a(\nu)}}(y)$ is the probability density corresponding to a rain depth of y mm occurring in ν storms; and $P_\theta(\nu)$ is the discrete probability mass of having exactly ν storms in a given year.

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Equation (2) represents the probability density that the sum of the rainfall depths contributed by ν annual storms adds up to exactly y mm, weighted by the discrete probability of having ν storms in that year. We followed Eagleson (1978) in modelling the occurrence of storm events as a Poisson process in order to determine the discrete probability (or probability mass) of having ν storm events over a period of length t:

$$P_\theta(\nu) = \frac{(\varpi t)^\nu \cdot e^{-\varpi t}}{\nu!} \qquad \nu = 0, 1, 2, \ldots \tag{3}$$

The single parameter in this distribution ϖ represents the average rate of arrival or occurrence of events, whilst its inverse ϖ^{-1}, corresponds to the average time elapsed between the beginning of two consecutive events. In our analysis t is a whole calendar year, but in semi-arid and arid climates it would represent the duration of the wet season within the year.

To obtain $f_{P_{a}(\nu)}(y)$ in Eq. (2) it is necessary to prescribe the probability distribution of precipitation depths of the iid events. For this Eagleson (1978) chose the Gamma distribution with two parameters λ and κ, because of its versatility and its regenerative property. The latter means that the sum of n iid Gamma(λ, κ) variables also has a Gamma distribution with parameters ($\lambda, n\kappa$) such that the mean storm depth is then $m_H = \kappa/\lambda$ and its variance $\sigma_H^2 = \kappa/\lambda^2$. The density function of total precipitation y from ν storms $f_{P_{a}(\nu)}(y)$ can then be expressed as:

$$f_{P_{a}(\nu)}(y) = \frac{\lambda \cdot (\lambda y)^{\nu\kappa - 1} \cdot e^{-\lambda y}}{\Gamma(\nu\kappa)} \quad y > 0, \tag{4}$$

where $\Gamma(x)$ is the gamma function.

Replacing the expressions for $P_\theta(\nu)$ and $f_{P_{a}(\nu)}(y)$ in Eq. (2) yields the probability density function of annual precipitation as (Eagleson, 1978):

$$f_{P_a}(y) = \sum_{\nu=1}^{\infty} \frac{\lambda \cdot (\lambda y)^{\nu\kappa - 1} \cdot e^{-\lambda y}}{\Gamma(\nu\kappa)} \cdot \frac{(\varpi t)^\nu \cdot e^{-\varpi t}}{\nu!} \quad y > 0. \tag{5}$$

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Integrating Eq. (5) results in the cumulative distribution function (cdf) for annual precipitation (Eagleson, 1978):

$$F_{P_\mathrm{a}}(y) = e^{-\varpi t} + \sum_{\nu=1}^{\infty} \frac{(\varpi t)^{\nu} \cdot e^{-\varpi t}}{\nu!} P[\nu\kappa, \lambda y] \qquad y \geq 0, \tag{6}$$

where $P[\nu\kappa, \lambda y]$ is Pearson's incomplete Gamma function.

2.4 Performance of the DDA

If long records are available, e.g., at least 25 ∼ 30 years, then key statistics and the distribution of annual precipitation totals can be estimated from data. For example, in temperate, humid areas, annual precipitation typically follows a normal or a log-normal distribution which can be fitted to data (e.g., Linsley et al., 1982; Markovic, 1965). On the other hand, the DDA summarised above allows for the description of annual precipitation based only on storm statistics (mean number of storms in a year, mean and variance of event depth), which can be estimated from short records provided these have a sufficiently high temporal resolution to accurately describe event properties. We assess the performance of the DDA vs. traditional model fitting to annual precipitation data with two important effects in mind.

First is the effect of record length, i.e., the uncertainty and bias which comes from using short precipitation records both for the traditional and derived distribution approaches. To this end we randomly subsample shorter records from the original series in Concepción and Lugano, to which we apply both methods. Instead of using independent continuous records (Pranzini, 2000; Pranzini and Meier, 2001), which would yield only a handful of subsamples, the analyses were carried out after resampling 200 n year datasets, where n is the number of different, randomly picked years that constitute each subsample ($n = 3, 5, 7, 10, 15$ years). This allows us to generate enough subsamples to draw statistically significant conclusions from the results.

Second is the effect of data resolution. At many locations precipitation is observed only once a day, so that higher resolution, continuously-gauged records are not avail-

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able. Thus, it is interesting to test how applicable the DDA is when using such low-resolution data. To this end we aggregated the continuously gauged data every 24 h (between 08:00 LT in a given day and 08:00 LT next day) as is commonly done in meteorological practice. When decreasing the data resolution, the MIT was accordingly changed to 1 day, for both Concepción and Lugano, to accommodate the minimum identifiable dry spell under the new scenario.

In summary, we worked with 2 types of precipitation data: continuously-recorded and aggregated every 24 h. We also considered 5 shorter record durations ranging from 3 to 15 years, on top of the full (25 or 32 year long) time-series. For each combination of data type and series length, we identified all storm events in the series, extracted their external characteristics, and then fitted exponential and Gamma distributions to their interarrival times and total precipitation depths, respectively. In this way, we obtained the derived distribution of annual precipitation for all of the datasets, at both study sites. We also fit normal and log-normal pdfs to the same datasets (the "traditional" approach), and then conducted two comparisons: (i) between the traditional methodology and the proposed DDA, and (ii) within the DDA, between using continuously-gauged rainfall data and daily data.

3 Results

3.1 Event properties

Storm events in Concepción are dominated by mid-latitude extra-tropical cyclones, which produce fronts resulting in low to mid-intensity rainfall events that occur throughout the year, but with higher frequency and magnitude during the winter months (Falvey and Garreaud, 2007). When using a 12 h MIT in order to discriminate independent storms, we obtained a total of 1350 rainfall events over the 1975–1999 period, neglecting storms with a total depth below 1 mm. In this case, the Gamma distribution with parameters $\lambda = 0.02784\,\text{mm}^{-1}$, and $\kappa = 0.6157$, fits the storm depth data very well.

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Likewise, an exponential distribution with parameter $\varpi = 0.006261\,\text{h}^{-1}$ adequately fits the interarrival times. Both marginal distributions are shown in Fig. 2.

In Lugano, storms are dominated by local-scale convective systems in the summer and fall which produce mid to high intensity showers during a few hours, which can be accentuated by orographic effects (Schiesser et al., 1995; Panziera et al., 2014). Consequently, a 4 h MIT was chosen, resulting in 1794 independent storms over the 1981–2012 period, neglecting storms with a total depth below 1 mm. Storm depths are fitted with a Gamma distribution with parameters $\lambda = 0.0255\,\text{mm}^{-1}$, and $\kappa = 0.3281$, while the interarrival times are fitted with an exponential distribution with parameter $\varpi = 0.0136\,\text{h}^{-1}$ as shown in Fig. 3.

3.2 Effect of record length

At Concepción and Lugano, for the entire records, we obtained the pdfs of annual precipitation using the DDA, based on the marginal distributions for storm counts and depths, and compared them with fitting normal and log-normal distributions (Fig. 4). At both locations, there are no significant differences between the three different distributions, at least in the range where the bulk of the data lies. We found that generally normal and log-normal distributions yielded very similar results. For this reason, we omit the log-normal results from the rest of this paper.

The sampling of shorter records was conducted on an annual basis in order to maintain seasonal coherence within a given year, i.e., years were selected at random and all storms within those years were sampled. This sampling destroys any correlation in precipitation between years if it exists. We verified the lack of temporal correlation in annual precipitation using Kendall's τ statistic (Ferguson et al., 2000) for lag-1 autocorrelation. In Concepción, Kendall's $\tau = -0.1522$ (p value $= 0.3128$) for $n = 25$ years. For Lugano Kendall's $\tau = 0.0151$ (p value $= 0.9195$) for $n = 32$ years. The null hypothesis that there is no autocorrelation is not rejected in either case. This justifies the sampling of storms into shorter records based on whole years.

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The consequences of reducing record lengths to $n = 5$ and $n = 10$ years are shown in Figs. 5 and 6 for Concepción, and Figs. 7 and 8 for Lugano, respectively. At both locations the results show a clear increase in dispersion of the pdfs of annual precipitation with shorter records, but the variability is significantly lower when using the DDA. The results for other subsample sizes ($n = 3, 7, 15$) show the same tendency. The reproduction of the standard deviation of annual precipitation in Fig. 9 clearly shows that the DDA dramatically reduces the uncertainty in this estimate of interannual variability for shorter record lengths.

In hydrological practice, we commonly fit distributions in order to estimate quantiles with a low frequency of occurrence but high magnitude. Because of the versatility in the shape of the derived distribution (Eq. 5), the DDA results in a lower bias and reduced uncertainty as compared with fitting a Normal distribution. These results are presented in Tables A1–A4, where we show the values of annual precipitation for different return periods, as computed with both methods for all record lengths, using continuously recorded data, both in Concepcioń and Lugano. The tables show the mean, standard deviation and skewness, as well as 10 selected quantiles, obtained with the DDA and fitting a normal PDF. These statistics are computed for both the complete records and the resampled, shorter records, in which case the mean and standard deviation of 200 samples are presented.

The uncertainty in estimating the variability of annual precipitation from short records is very large if only annual totals are used. The DDA for the same short records, based on using event properties, significantly reduces this uncertainty.

3.3 Effect of data resolution

Most weather stations world-wide are not equipped with continuously recording rain gauges; in such cases precipitation is usually measured only once per day. In order to test the suitability of daily rainfall data in the DDA, we totalized our high resolution data over 24 h long periods and then applied the DDA to these daily data. Figure 10 shows that when we use daily instead of continuously recorded precipitation data we obtain

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similar values for the central tendency indicators, but the extremes of the distribution show important biases.

This occurs when combining the use of aggregated data and a shorter record length as well, as shown in Figs. 11 and 12 at both stations. The spread of annual precipitation increases both with reducing the record length as well as by aggregating data, which may lead to an important bias especially in wet years. This result points to the benefits of installing high-resolution gauges to derive accurate storm statistics as well as to the limited value of short daily records for deriving reliable precipitation statistics at the annual scale.

4 Discussion and conclusions

The distributions of annual precipitation obtained with Eagleson's (1978) derived distribution approach, DDA, are very similar to the fitting of a normal or log-normal distribution when using complete, continuously-recorded time series (Fig. 4). Thus, whenever a long rainfall record is available and the homogeneity issue has been dealt with, the traditional approach of fitting a normal or log-normal distribution is adequate. On the other hand, the amount of information used in the DDA is much greater, because it explicitly includes statistics from many storm events that occur within the years, instead of only annual sums. This allows for a much better estimation of the three parameters of the model and reduces the uncertainty in the estimates.

More importantly, the DDA still yields good results when attempting to estimate the annual rainfall distribution with shorter records, as long as these consist of continuous data, as shown in Figs. 5 and 6. Shorter records yield larger variability in annual precipitation, but measures of both the central tendency and dispersion are still consistent with those estimated using all of the information available. This is because even if, say only 3 years of data are available, there is still a sufficiently large number of rainfall events (average of 54 yearly storms for Concepción and 119 for Lugano) to allow for a good probabilistic description of their external characteristics.

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On the other hand, when one attempts to fit a normal distribution to only a few annual rainfall data points (Figs. 5 and 6), there is a large uncertainty in the estimates. Indeed, interannual variability is estimated better with only 3 or 5 years of continuously recorded data by DDA than it is with much longer annual records only (Fig. 9). Furthermore, years with incomplete records may still be used with DDA in order to extract storm properties and estimate model parameters, while for fitting a distribution to annual totals only complete years can be used. Results also show that when only daily rainfall records are available, however, a bias is introduced (Figs. 10–12). Therefore, the use of low-resolution data for DDA cannot be recommended.

Overall, our results show that Eagleson's derived distribution approach is a better way of estimating the probability distribution of annual precipitation, especially when only a short high-resolution record is available, because the uncertainty in estimates is reduced. The importance of these results lies not only in the possibility of estimating annual rainfall and its variability when short time series are available; it also allows to study the long-term behaviour of annual precipitation (even when long time series are available) by using shorter records that guarantee homogeneity of the data.

An important conclusion of this work is that installing high-resolution (hourly or less) precipitation gauges in previously ungauged locations, even for short periods, has tangible benefits for the estimates of long-term precipitation statistics, such as interannual variability and quantiles of annual precipitation with high return periods at those locations. This is important because accurate gauge-level precipitation estimates remain vital for the correction of remotely sensed data and merging different precipitation data types, e.g., weather radar, satellite, etc. (e.g., Xie and Arkin, 1996), and for the spatial interpolation of precipitation, especially in areas with complex topography (e.g., Masson and Frei, 2014).

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Table A1. Quantiles of the distribution of annual rainfall in Concepción, as obtained with different record lengths resampled 200 times and continuous data using derived distributions (in mm).

Sample Size		Mean	STD	Skew.	Quantiles									
					Q .01	Q .02	Q .05	Q .10	Q .20	Q .80	Q .90	Q .95	Q .98	Q .99
25 years		1213.6	265.4	0.35	670	727	817	900	1006	1451	1579	1688	1814	1900
15 years	m	1209.8	264.9	0.35	667	725	814	897	1002	1447	1575	1683	1809	1895
	s	39.5	8.0	0.01	27.1	28.4	30.3	32.1	34.5	45.3	48.5	51.4	54.7	57.0
10 years	m	1217.3	266.2	0.35	672	730	820	903	1009	1456	1584	1693	1820	1906
	s	60.0	13.2	0.01	38.8	40.9	44.2	47.3	51.5	70.2	75.9	80.8	86.6	90.5
7 years	m	1214.0	264.8	0.35	672	729	818	902	1007	1451	1579	1687	1813	1899
	s	82.1	17.6	0.02	53.9	56.6	61.0	65.2	70.7	95.5	103.0	109.5	117.1	122.4
5 years	m	1205.0	263.8	0.35	665	722	811	894	998	1442	1569	1677	1802	1888
	s	99.1	21.2	0.02	66.4	69.6	74.6	79.5	85.9	114.9	123.8	131.4	140.6	146.9
3 years	m	1242.2	271.1	0.35	687	746	837	922	1030	1485	1616	1727	1856	1944
	s	140.7	28.1	0.04	98.4	102.5	109.2	115.4	123.6	160.6	171.8	181.6	193.2	201.2

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Table A2. Quantiles of the distribution of annual rainfall in Concepción, as obtained with different record lengths resampled 200 times fitting normal distributions (in mm).

Sample Size		Mean	STD	Quantiles									
				Q .01	Q .02	Q .05	Q .10	Q .20	Q .80	Q .90	Q .95	Q .98	Q .99
25 years (DDA)		1213.6	265.4	670	727	817	900	1006	1451	1579	1688	1814	1900
25 years (Normal)		1194.1	269.8	566	640	750	848	967	1421	1540	1638	1748	1822
15 years	m	1189.8	270.2	561	635	745	843	962	1417	1536	1634	1745	1818
	s	42.3	28.2	80.9	74.5	65.3	57.8	50.1	46.8	53.4	60.3	69.0	75.2
10 years	m	1197.9	271.7	566	640	751	850	969	1427	1546	1645	1756	1830
	s	63.8	42.6	123.7	113.9	99.9	88.4	76.6	69.7	79.3	89.5	102.5	111.9
7 years	m	1194.9	264.4	580	652	760	856	972	1417	1534	1630	1738	1810
	s	87.6	60.1	172.8	158.8	138.9	122.7	105.8	96.4	110.3	124.9	143.6	156.9
5 years	m	1186.7	266.4	567	640	749	845	963	1411	1528	1625	1734	1807
	s	104.1	75.5	215.6	197.8	172.2	151.2	128.9	114.5	132.4	151.1	174.9	191.9
3 years	m	1224.2	242.2	661	727	826	914	1020	1428	1535	1623	1722	1788
	s	152.0	115.9	325.2	297.6	257.8	225.0	190.3	170.4	199.3	229.1	266.6	293.2

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Table A3. Quantiles of the distribution of annual rainfall in Lugano, as obtained with different record lengths resampled 200 times and continuous data using derived distributions (in mm).

Sample Size		Mean	STD	Skew.	Quantiles									
					Q .01	Q .02	Q .05	Q .10	Q .20	Q .80	Q .90	Q .95	Q .98	Q .99
32 years		1529.8	280.0	0.27	942	1006	1105	1197	1311	1786	1919	2032	2163	2252
15 years	m	1531.2	270.8	0.27	960	1023	1120	1208	1319	1778	1907	2016	2142	2227
	s	60.4	8.3	0.03	44.1	45.9	48.8	51.4	54.7	68.9	72.9	76.3	80.3	83.1
10 years	m	1520.5	268.6	0.27	955	1017	1112	1200	1310	1765	1893	2001	2126	2210
	s	71.5	10.2	0.03	52.7	54.8	58.1	61.1	64.9	81.4	86.2	90.3	95.0	98.3
7 years	m	1531.6	269.8	0.26	962	1024	1121	1210	1321	1779	1908	2017	2143	2228
	s	101.8	14.7	0.05	73.8	76.9	81.9	86.5	92.5	117.9	125.3	131.6	139.0	144.0
5 years	m	1532.0	268.8	0.25	964	1026	1123	1211	1322	1780	1908	2017	2142	2228
	s	121.1	16.5	0.07	89.0	92.7	98.4	103.9	110.7	140.1	148.6	155.9	164.4	170.1
3 years	m	1529.5	267.4	0.24	963	1025	1121	1210	1320	1778	1906	2015	2140	2225
	s	150.9	21.4	0.09	110.2	114.9	122.2	129.2	137.9	175.8	186.8	196.3	207.2	214.8

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Table A4. Quantiles of the distribution of annual rainfall in Lugano, as obtained with different record lengths resampled 200 times fitting normal distributions (in mm).

Sample Size		Mean	STD	QUANTILES Q .01	Q .02	Q .05	Q .10	Q .20	Q .80	Q .90	Q .95	Q .98	Q .99
32 years (DDA)		1529.8	280.0	942	1006	1105	1197	1311	1786	1919	2032	2163	2252
32 years (Normal)		1530.5	290.1	856	935	1053	1159	1286	1775	1902	2008	2126	2205
15 years	m	1530.5	280.2	879	955	1070	1171	1295	1766	1890	1991	2106	2182
	s	56.8	43.7	101.9	92.1	78.4	68.0	58.6	75.6	90.0	103.1	118.6	129.3
10 years	m	1521.7	281.6	867	943	1058	1161	1285	1759	1883	1985	2100	2177
	s	69.0	62.0	137.7	123.1	102.4	86.2	71.3	99.5	121.4	141.0	163.9	179.5
7 years	m	1530.0	276.0	888	963	1076	1176	1298	1762	1884	1984	2097	2172
	s	98.8	81.6	177.4	158.8	132.9	113.2	96.4	140.1	169.0	194.6	224.6	245.1
5 years	m	1532.6	264.0	918	990	1098	1194	1310	1755	1871	1967	2075	2147
	s	116.4	103.6	239.7	215.2	180.5	152.9	126.6	162.0	197.3	229.2	266.9	292.7
3 years	m	1530.0	258.8	928	999	1104	1198	1312	1748	1862	1956	2062	2132
	s	141.9	135.2	322.9	290.1	243.2	205.0	166.6	196.1	241.5	282.9	332.1	365.8

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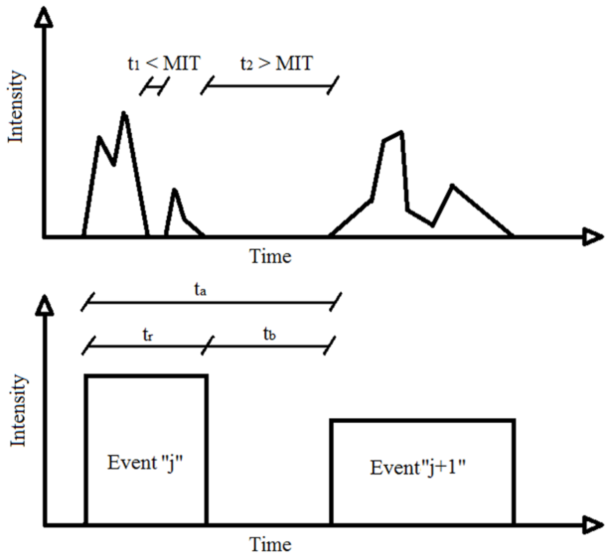

Figure 1. External independent-storm properties obtained from the rain gauge records.

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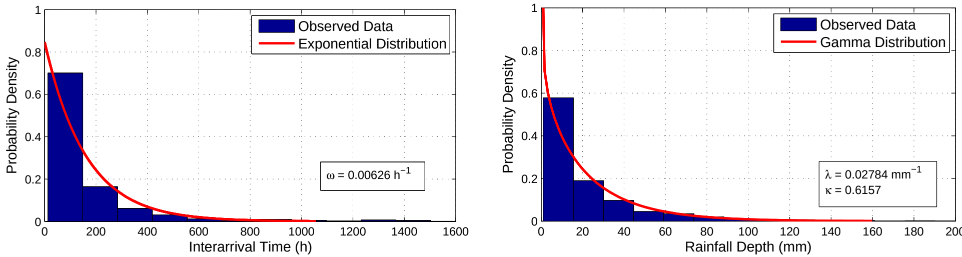

Figure 2. Fitted distributions to rainfall depths (left) and interarrival times (right) for 25 years of data in Concepción.

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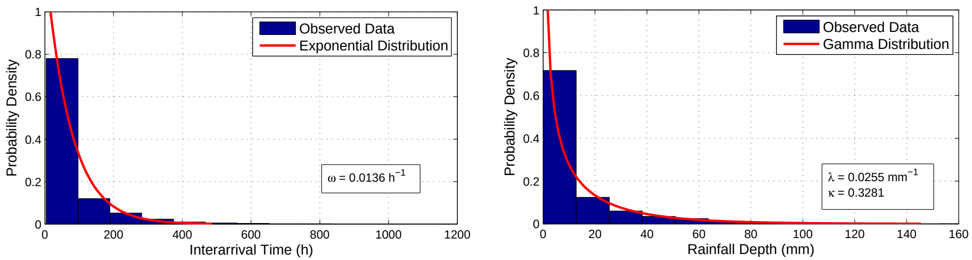

Figure 3. Fitted distributions to rainfall depths (left) and interarrival times (right) for 32 years of data in Lugano.

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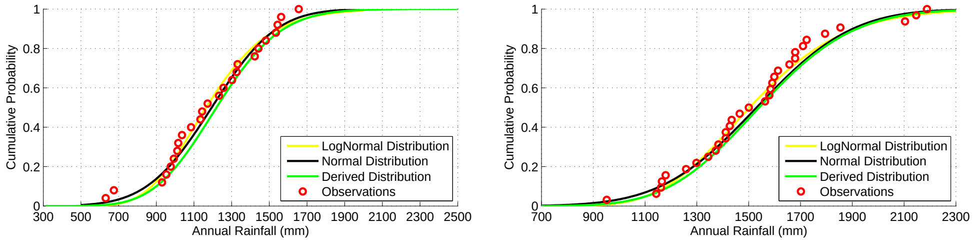

Figure 4. Cumulative distributions derived with the DDA and fitted as a normal and log-normal distribution to annual precipitation totals for Concepción, Chile (left) and Lugano, Switzerland (right).

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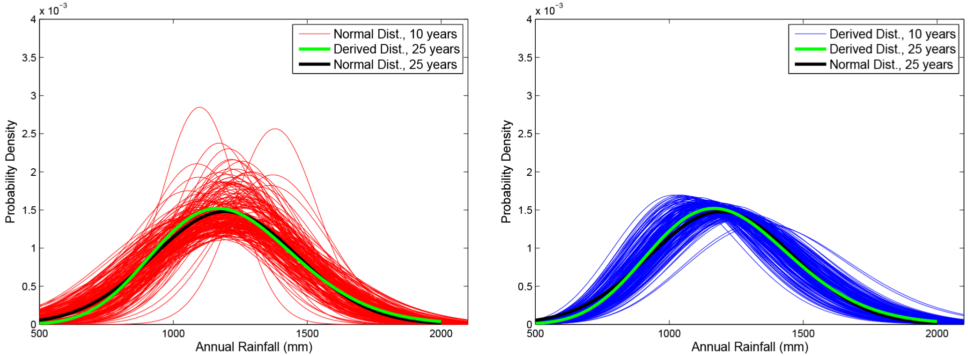

Figure 5. Estimated PDFs for 10 year subsamples using Normal Distributions (red, left) and Derived Distributions (blue, right) in Concepción.

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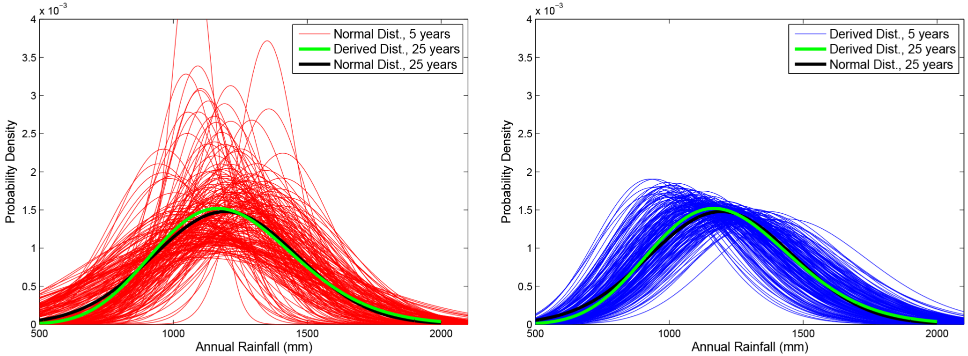

Figure 6. Estimated PDFs for 5 year subsamples using Normal Distributions (red, left) and Derived Distributions (blue, right) in Concepción.

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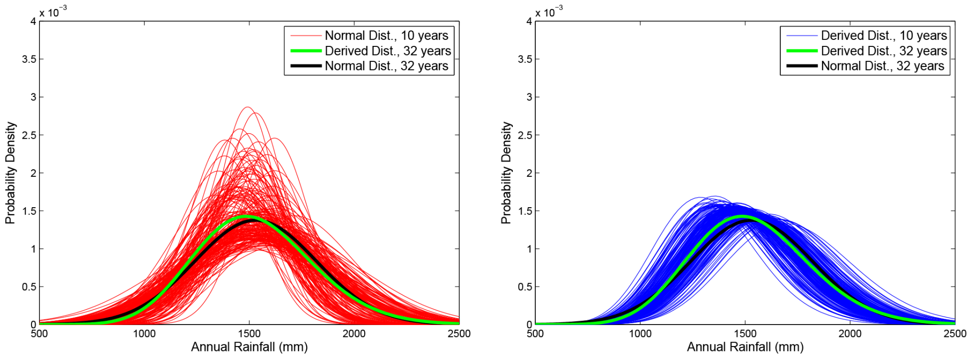

Figure 7. Estimated PDFs for 10 year subsamples using Normal Distributions (red, left) and Derived Distributions (blue, right) in Lugano.

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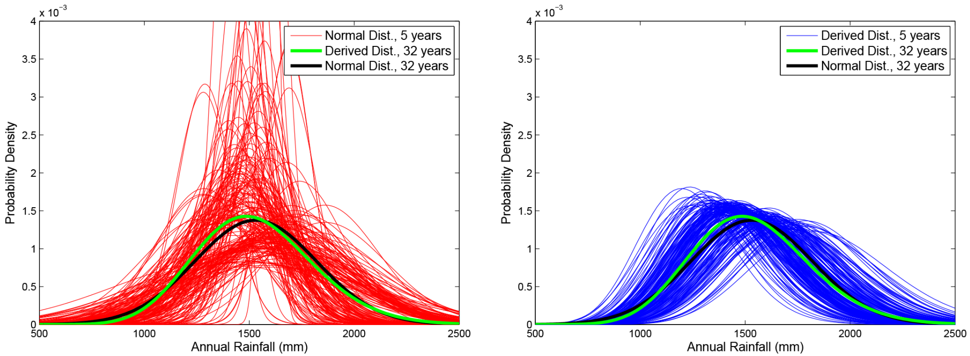

Figure 8. Estimated PDFs for 5 year subsamples using Normal Distributions (red, left) and Derived Distributions (blue, right) in Lugano.

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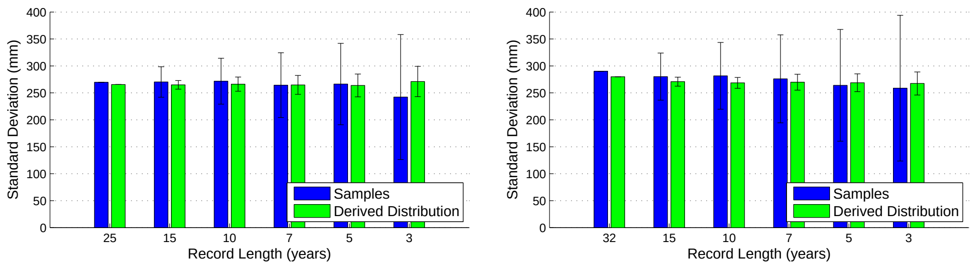

Figure 9. Sample standard deviations of annual precipitation computed from yearly totals (in blue), compared to the corresponding population standard deviations estimated with the DDA (in green). For record lengths ≤ 15 yr, the whiskers show the range ±1 SD from resampling ($n = 200$). Concepción is on the left and Lugano on the right.

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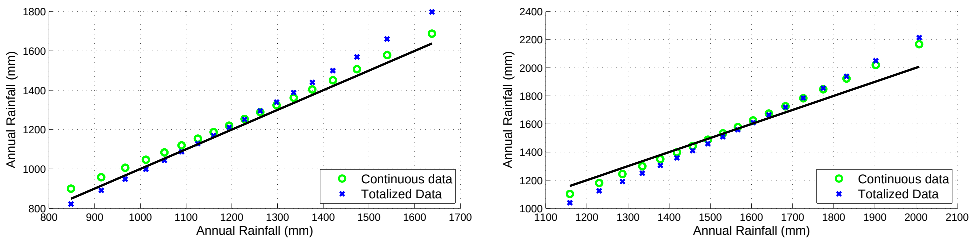

Figure 10. Effects of data resolution on the distributions obtained with Derived Distributions for Concepción (left) and Lugano (right).

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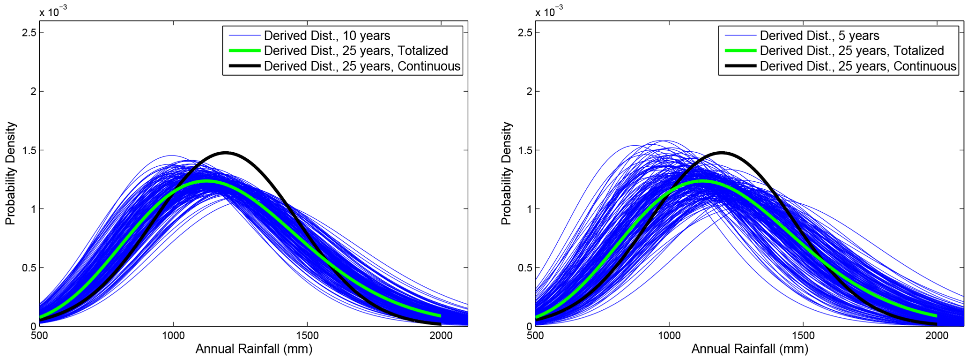

Figure 11. Estimated PDFs for 10 year (left) and 5 year (right) subsamples using a 24 h totalized record in Concepción.

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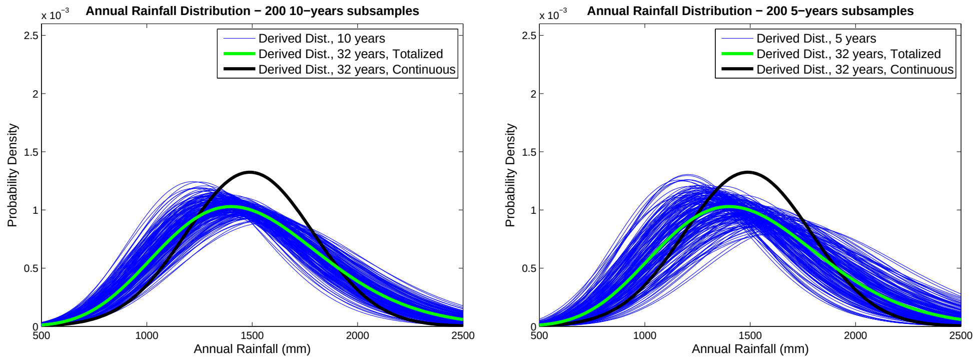

Figure 12. Estimated PDFs for 10 year (left) and 5 year (right) subsamples using a 24 h totalized record in Lugano.

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