

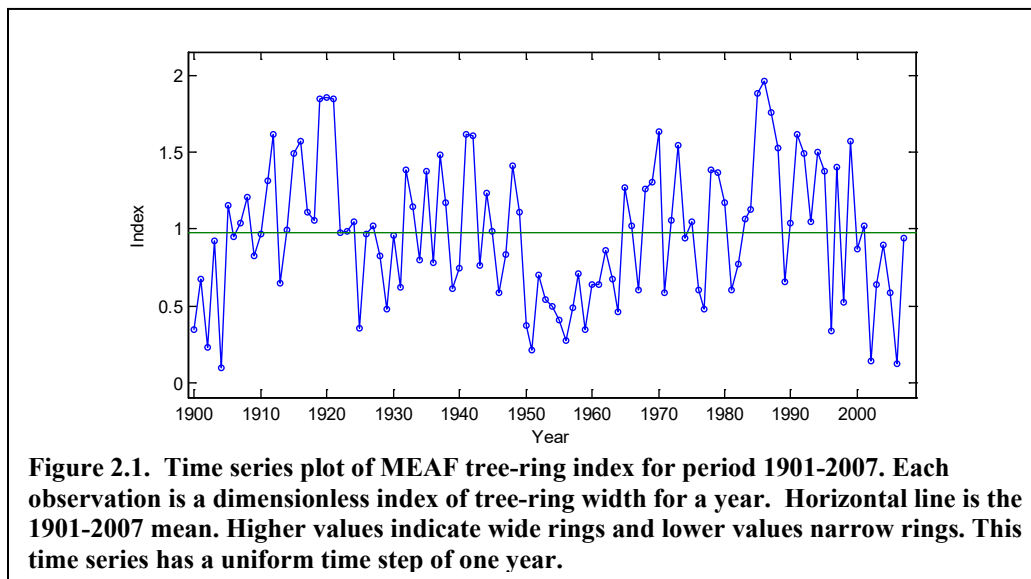
2 Probability distribution

The probability distribution of a time series describes the probability that an observation falls into a specified range of values. An empirical probability distribution for a time series can be arrived at by sorting and ranking the values of the series. Quantiles and percentiles are useful statistics that can be taken directly from the empirical probability distribution. Many parametric statistical tests assume the time series is a sample from a population with a particular population probability distribution. Often the population is assumed to be normal. This chapter presents some basic definitions, statistics and plots related to the probability distribution. In addition, a test (Lilliefors test) is introduced for testing whether a sample comes from a normal distribution with unspecified mean and variance.

2.1 Definitions

Time series

A *time series* is a set of observations ordered in time. We will consider only time series observed at a discrete set of evenly spaced time intervals: x_t at times $t = 1, 2, \dots, N$, where N is the length of the time series. Annual indices of tree-ring width are one example of a time series (Figure 2.1).



Random variable

A random variable is a function that assigns real numbers to the points in a sample space. The random variable is usually denoted by a capital letter (e.g., X), and the value it takes by a small letter (e.g., x).

Probability function (also called probability density function)

The probability function of the random variable X , denoted by $f(x)$ is the function that gives the probability of X taking the value x , for any real number x :

$$f(x) = P(X = x) \quad (1)$$

The most commonly used theoretical distribution is the normal distribution. Its probability density function (pdf) is given by:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{(x-\mu)^2}{2\sigma^2} \right] \quad (2)$$

where μ and σ are the population mean and standard deviation of X . The standard normal distribution is the normal distribution with $\mu=0$ and $\sigma=1$. A plot of the standard normal pdf is a bell-shaped curve (Figure 2.2).

Distribution function (also called cumulative distribution function (cdf))

The distribution function of a random variable X is the function that gives the probability of X being less than or equal to a real number x :

$$F(x) = p(X \leq x) = \sum_{u \leq x} f(u) \quad (3)$$

For a theoretical distribution, the cdf can be computed as the integral of the probability density function. The cdf of standard normal has an “S-shaped” form (Figure 2.3).

Empirical distribution function, or empirical cdf

Let x_1, x_2, \dots, x_n be a sample of some random variable. The *empirical distribution function* $S(x)$ is a function of x , which equals the decimal fraction of the observations that are less than or equal to x_c for $-\infty < x_c < \infty$.

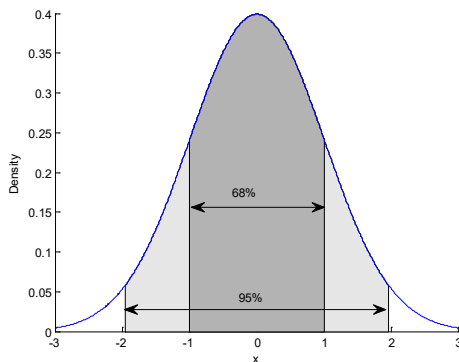


Figure 2.2. Probability density function of standard normal distribution. Sixty-eight percent of the population is within ± 1.0 of zero. Ninety-five percent is within ± 1.96 of zero.

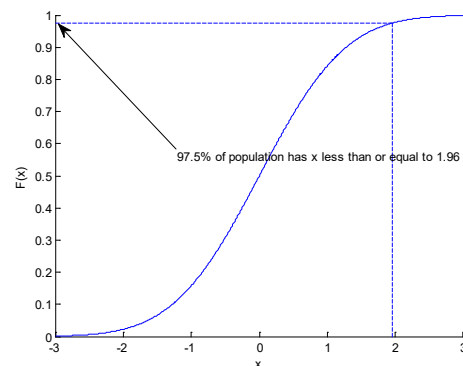


Figure 2.3. Cumulative distribution function (cdf) of standard normal distribution.

Statistical and deterministic

A time series is *deterministic* if its future behavior can be exactly predicted from its past behavior. Otherwise the time series is *statistical*. The future behavior of a statistical time series can be predicted only in probabilistic terms. We will consider only statistical time series.

Process

A statistical time series can theoretically be viewed as generated by some underlying statistical *process*. Sometimes the term *stochastic* is used instead of statistical; the two terms are synonyms. The process might be represented as a mathematical model. The time series can be considered a single *realization* of the generating process.

Stationarity

The process can be viewed as potentially generating an infinite number of time series. The observed series x_t is just one possible realization. The value of the series x_t at any time $t = i$ can be considered a realization of a random variable X_i , with a probability density function $p(x_i)$. Any set of X_i at different times, say $\{X_{j_1}, \dots, X_{j_r}\}$, has a joint probability density function. If the joint probability density function is independent of time, the process is said to be *strictly stationary*. Many statistical procedures assume at least *weak stationarity*, which means that the mean, variance, and autocovariance function are independent of time. For Gaussian processes, weak stationarity implies strict stationarity.

Chatfield (2004) introduces the idea of stationarity from an intuitive point of view: “Broadly speaking, a time series is said to be stationary if there is no systematic change in mean (no trend), if there is no systematic change in variance and if strictly periodic variations have been removed. In other words, the properties of one section of the data are much like those of any other section.” Such an intuitive view basically amounts to observing that the properties of the series appear to be consistent with a stationary generating process or model.

2.2 DESCRIPTIVE STATISTICS

Sample mean, variance, standard deviation

Let x_1, x_2, \dots, x_N be a time series of length N . The *mean*, *variance*, and *standard deviation* are defined by

$$\bar{x} = \frac{1}{N} \sum_{t=1}^N x_t \quad \text{mean} \quad (4)$$

$$s^2 = \frac{1}{N} \sum_{t=1}^N (x_t - \bar{x})^2 \quad \text{variance} \quad (5)$$

$$s = \sqrt{\frac{1}{N} \sum_{t=1}^N (x_t - \bar{x})^2} = \sqrt{s^2} \quad \text{standard deviation} \quad (6)$$

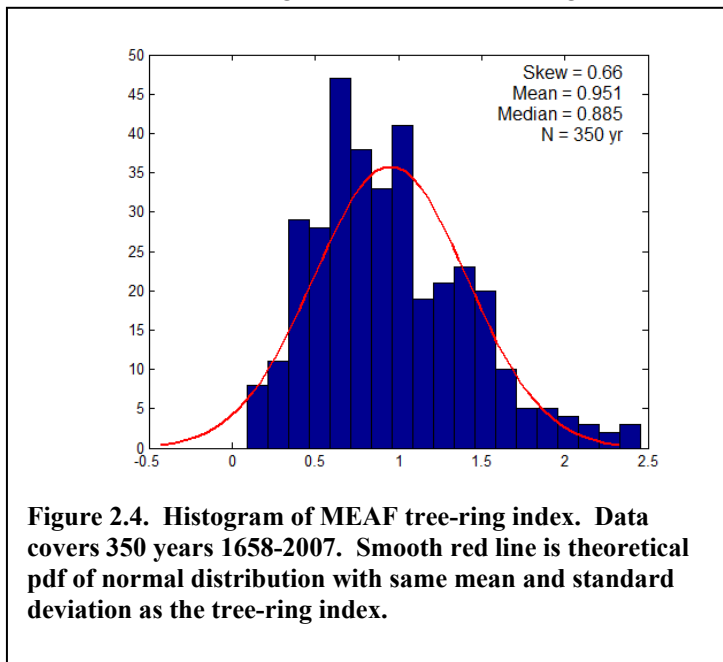
The sample standard deviation and variance are sometimes written with $N - 1$ replacing N in the denominators of (5) and (6) so that the sample statistics are unbiased estimators of the population parameters.

Sample skewness

The *shape* of a data distribution loosely refers to its symmetry in a histogram, or bar plot of number observations falling into various ranges of data values. A statistic summarizing the shape in terms of symmetry of the histogram is the sample skewness. Skewness is defined as the third central moment (the average cubed departure from the mean) divided by the cube of the standard deviation:

$$g = \frac{\frac{1}{N} \sum_{i=1}^N (x - \bar{x})^3}{s^3} \quad (7)$$

If $g = 0$, the distribution is symmetric around \bar{x} . If $g > 0$, the distribution has positive skew, or is skewed to the right. If $g < 0$, the distribution has negative skew, or is skewed to the left. An alternative description of skew is given by the relative positions of the mean and mode. The mode is the most common value, or the peak in the histogram. Mean greater than mode is positive skew; mean less than mode is negative skew (Panofsky and Brier, 1968). In general for positive skew, mean > median > mode. The opposite is true for negative skew: mean < median < mode. Figure 2.4 shows the histogram of a time series with slight positive skew.



Location and spread

The *location* is the “center” of the data. The data typically clusters around some point that defines this center. The mean and median are two commonly used measures of location. The *spread* describes the variability of the data. The standard deviation is one measure of the spread. Another is the *interquartile range*, which is the difference between the 75th and 25th percentiles of the data. The interquartile range is a robust measure of the spread because it is unaffected by changes in the upper and

lower 25% of the data. A measure of spread extremely sensitive to individual observations is the *range* – the difference between the highest and lowest value. Measures of spread are illustrated in a time series plot of a tree-ring index (Figure 2.5).

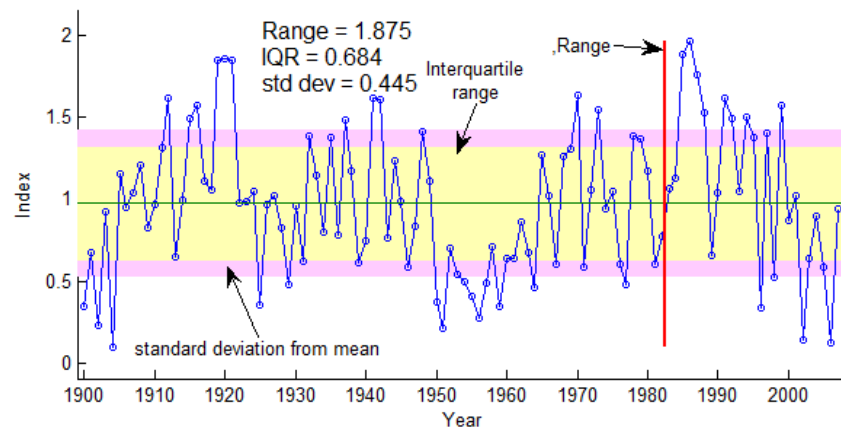


Figure 2.5. Measures of spread illustrated in time series plot of MEAF tree-ring index, 1901-2007. Plotted series same as in Figure 2.1. Range extends from highest to lowest value. Interquartile range (iqr) covers the middle 50% of observations (all except the highest 25% and lowest 25%). Standard deviation is computed from squared departures from mean; in this plot the purple band delineates observations within ± 1 standard deviation of the mean. For a normal distribution, 68% of the observations would fall within ± 1 standard deviation of the mean. It is therefore expected that for normally distributed data the iqr would be narrower than the band marking ± 1 standard deviations from the mean. In that sense, the MEAF is consistent with a normally distributed time series.

2.3 Basic Plots

This section introduces plots useful for an initial look at a time series and for analyzing location, spread and shape of the data distribution. Some useful plots are listed in Table 2.1.

Table 2.1 Basic plots useful for time series distribution assessment

Name of plot	Key Information	Matlab Functions
Time plot	Sequence, persistence	plot
Quantile plot	Non-exceedance probability	cdfplot
Box plot	Location, spread, shape	boxplot
Quantile-quantile plot (q-q plot)	Relative shape	qqplot
Normal probability plot	Normality	normplot
Histogram	Shape	hist, histfit

Time plot. The series plot (Figure 2.1, 2.5) is the single most important plot in time series analysis. Unlike the other plots described in this chapter, the time series plot retains the time-sequence of observations, and so graphically shows such features as persistence, trend in mean and trend in variance.

Quantile plot. The f quantile is the data value below which approximately a decimal fraction f of the data is found. That data value is denoted $q(f)$. Each data point can be assigned an f -value. Let a time series x of length n be sorted from smallest to largest values, such that the sorted values have rank $i = 1, 2, \dots, n$. The f -value for each observation is computed as

$$f_i = \frac{i - 0.5}{n}$$

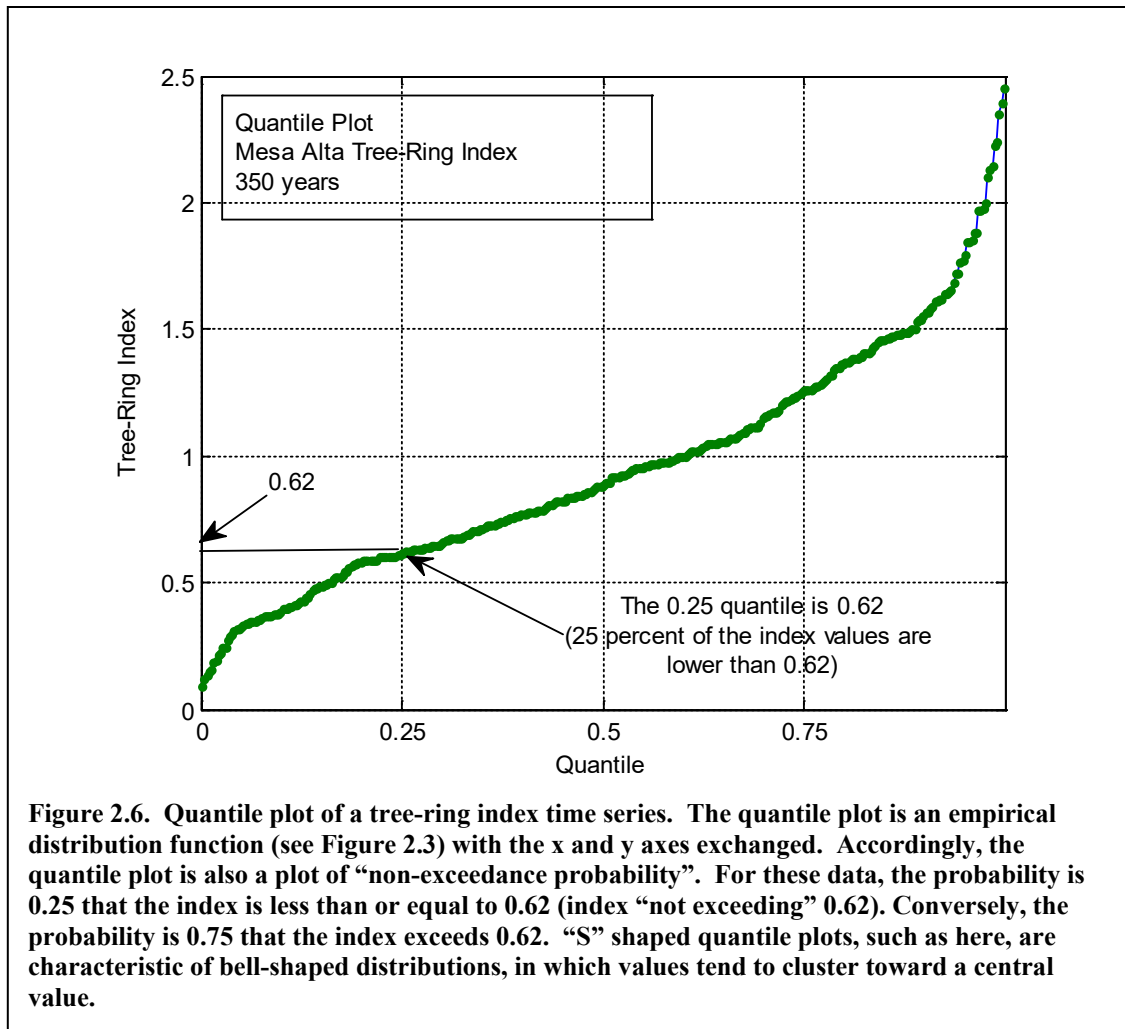
This equation gives the quantile for any observation. For example, if the series has 99 observations ($n = 99$), the smallest ranking data, with $f_1 = \frac{1 - 0.5}{99} = 0.0051$, is the “0.0051 quantile.” The middle-ranking, or 50th ranking value ($i = 50$) has $f_{50} = \frac{50 - 0.5}{99} = \frac{49.5}{99} = 0.50$, and is the 0.50 quantile.

The 0.5 quantile is also called the *median*. The 0.25 and 0.75 quantiles are called the *lower and upper quartiles*. The interquartile range (Figure 2.5) is defined as the difference between the upper and lower quartiles:

$$r = q(.75) - q(.25)$$

Half of the observations lie between the upper and lower quartiles.

Quantiles for f -values not corresponding exactly to an observation can be linearly interpolated from flanking quantiles that do correspond to observations. Figure 2.6 shows a sample quantile plot. Note that the quantile plot has exactly the same information as the cdf. The only difference is that the probability axis for the quantile plot is the abscissa instead of the ordinate.



Box plot. A box plot summarizes the data distribution primarily in terms of the median, the upper quartile, and lower quartile (Figure 2.7). The “box” by definition extends from the upper to lower quartile. Within the box is a dot or line marking the median. The width of the box, or the distance between the upper and lower quartiles, is equal to the interquartile range, and is a measure of spread. The median is a measure of location, and the relative distances of the median from the upper and lower quartiles is a measure of symmetry “in the middle” of the distribution. For example, the median is approximately in the middle of the box for a symmetric distribution, and is positioned toward the lower part of the box for a positively skewed distribution.

“Whiskers” are drawn outside the box at what are called the “*adjacent values*.” The upper adjacent value is the largest observation that does not exceed the upper quartile plus $1.5r$, where r is the interquartile range. The lower adjacent value is the smallest observation that is not less than the lower quartile minus $1.5r$. If no data fall outside this $1.5r$ buffer around the box, the

whiskers mark the data extremes. The whiskers also give information about symmetry in the tails of the distribution. For example, if the distance from the top of the box to the upper whisker exceeds the distance from the bottom of the box to the lower whisker, the distribution is positively skewed in the tails. Skewness in the tails may be different from skewness in the middle of the distribution. For example, a distribution can be positively skewed in the middle and negatively skewed in the tails.

Any points lying outside the $1.5r$ buffer around the box are marked by individual symbols as “outliers”. These points are outliers in comparison to what is expected from a normal distribution with the same mean and variance as the data sample. For a standard normal distribution, the median and mean are both zero, and:

$$\begin{aligned}q_{.25} &= -0.67449 \\q_{.75} &= 0.67449 \\r &= q_{.75} - q_{.25} = 1.349\end{aligned}$$

Where $q_{.25}$ and $q_{.75}$ are the first and third quartiles, and r is the interquartile range. From the preceding paragraph, we see that the whiskers for a standard normal distribution are at data values:

$$\begin{aligned}\text{Upper whisker} &= 2.698 \\ \text{Lower whisker} &= -2.698\end{aligned}$$

And from the cdf of the standard normal distribution, we see that the probability of a lower value than $x = -2.698$ is

$$p(X < -2.698) \approx 0.0035$$

This result shows that for a normal distribution, roughly 0.35 percent of the data is expected to fall below the lower whisker. By symmetry, 0.35 percent of the data are expected above the upper whisker. These data values are classified as outliers. Exactly how many outliers might be expected in a sample of normally distributed data depends on the sample size. For example, with a sample size of 100, we expect no outliers, as 0.35 percent of 100 is much less than 1. With a sample size of 10,000, however, we would expect 35 positive outliers and 35 negative outliers for a normal distribution. It is therefore not surprising to find some outliers in box plots of very large data sample, and the existence of a few outliers in samples much larger than 100 does not necessarily indicate lack of normality.

A “notched” boxplot is an extension to the simple boxplot intended to show the uncertainty in the median by the width of a notch on the side of the box. “Notched” boxplots plotted side by side can give some indication of the significance of differences in medians of two samples. Given a sample of data with N observations and interquartile range R , how wide should the notch in the box plot be for a) 95 percent confidence interval about the median, and b) visual assessment of whether two medians are statistically different at the 95 percent level? The Gaussian-based asymptotic approximation of the standard deviation s of the median M is given by

$$s = 1.25R / 1.35\sqrt{N}$$

This approximation “can be shown to be reasonably broadly applicable to other distributions.” The approximation holds especially if the middle of the distribution is shaped approximately like the Gaussian.

Because 1.96 standard deviations encloses 95% of a normal distribution, a notch about the median for a 95 % confidence interval can be drawn at

$$M = \pm 1.96s$$

For a “gap gauge” which would indicate significant differences in medians at the 95% level, 1.96 would generally be much too stringent. A better choice is for the notch at

$$M = \pm 1.7s$$

which is the width of notches drawn by Matlab.

McGill et al. (1978) stress that there are no hard and fast rules for notch width for comparing medians of two groups. The choice depends also on the standard deviations of the groups. If the standard deviations are vastly different, $M = \pm 1.96s$ is appropriate, while, while if the standard deviations are nearly equal, $M = \pm 1.3896s$ is appropriate. McGill et al. (1978) selected $M = \pm 1.7s$ as a compromise.

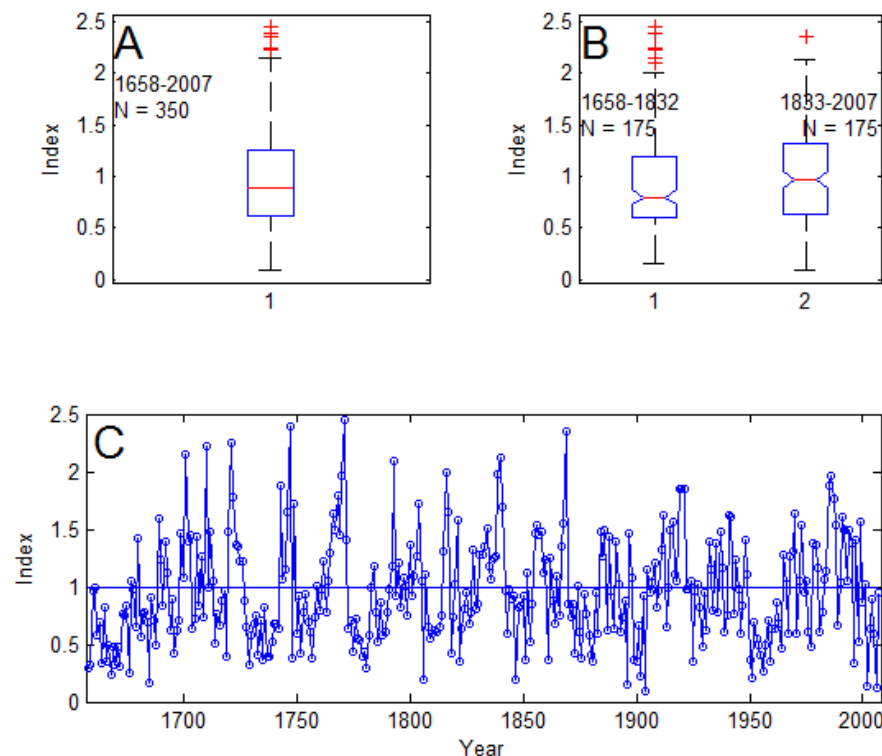
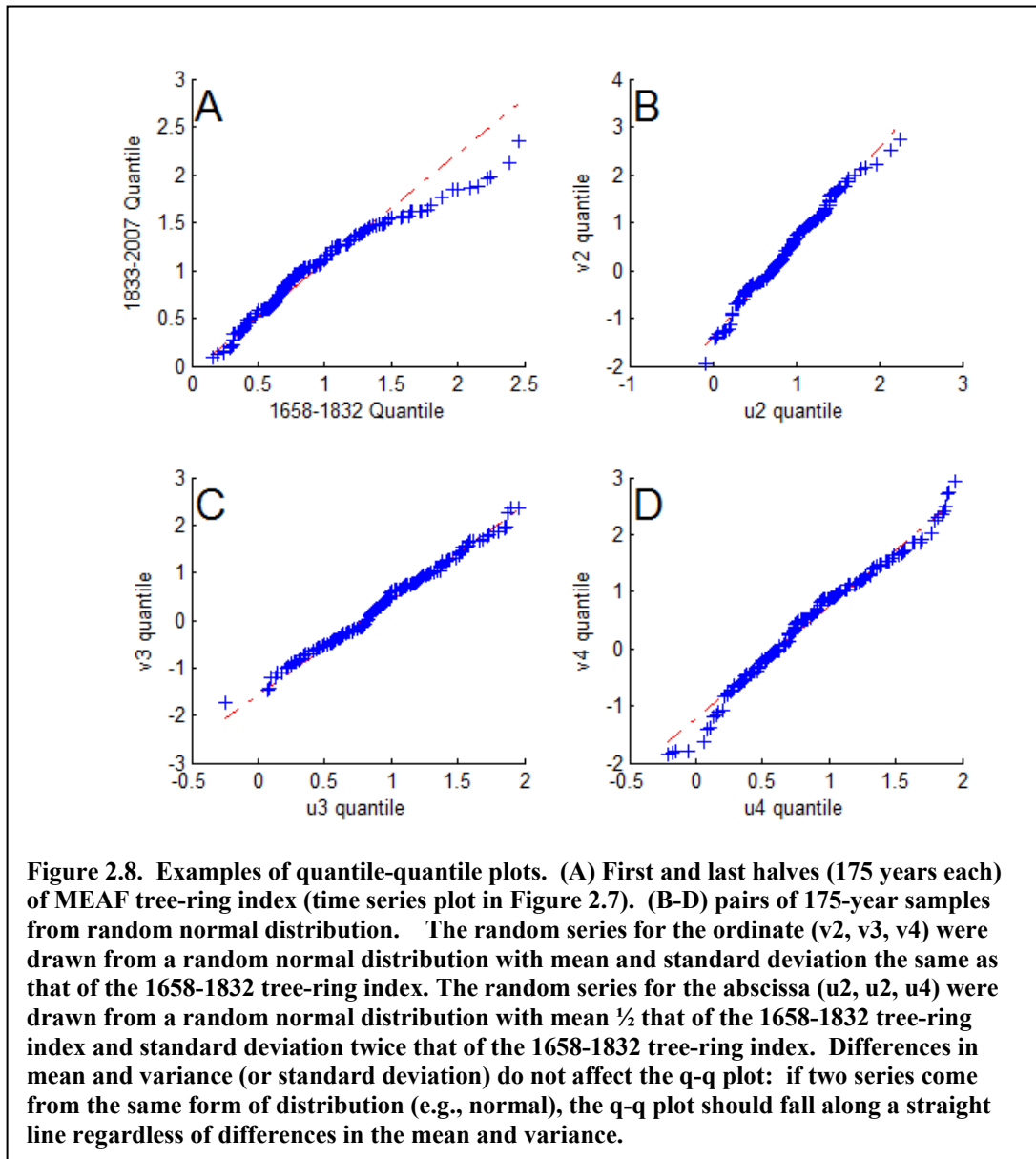


Figure 2.7. Boxplots and time series plot of tree-ring index for site MEAF. (A) Boxplot for entire series. (B) Notched boxplots for first and second halves of series. (C) Time series plot of entire series. Boxplot for entire series shows mild positive skew in middle of distribution (median toward lower half of box) and positive skew in tails. Boxplots for halves emphasize the relative skewness of first half. Notches that do not overlap indicate sub-period medians different at $\alpha=0.05$. Greater skew in the first half is obvious from the time series plot, but the difference in medians is not noticeable. In fact, median is 0.79 for first half and 0.96 for second half.

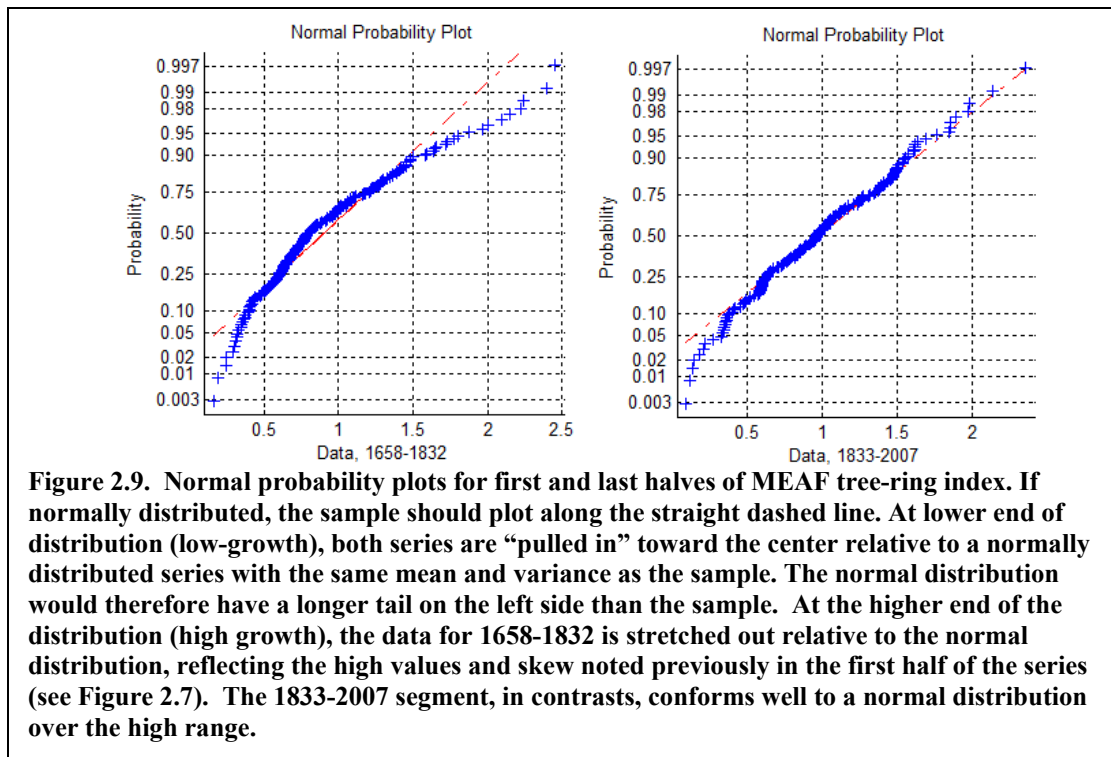
Quantile-quantile plot (q-q plot). The q-q plot compares the quantiles of two variables. If the variables come from the same type of distribution (e.g., normal), the qq-plot is a straight line. This is true even if the parameters of the distributions (e.g., mean, variance) differ. To help in evaluating the q-q plot, a straight line is usually drawn for reference on the plot. In Matlab, this line is drawn through the 0.25 and 0.75 quantiles, and is extended. A q-q plot of the second half (175 years) of the MEAF tree-ring index against the first half (Figure 2.8A) shows large departure

from the straight line toward the high-growth range of the data. Specifically, the same quantile has a higher tree-ring index for the first half of the data than for the last half. This departure reflects the difference in skew evident in the time series and box plots (Figure 2.7). It is important, however to consider random sampling variability in the interpretation of q-q plots. The departures in plots in Figure 2.8 B-D are due to sampling variability, as all series were drawn from the normal distributions.



Normal-probability plot. In the normal probability plot, the quantiles of a normally distributed variable with the same mean and variance as the data are plotted against the quantiles of the data. The y-axis is labeled with the z -values for the theoretical (normal) distribution rather than with the quantiles of the normal variate. The interpretation is analogous to that for the q-q plot: a straight line indicates the data come from a normal distribution. Curvature indicates departure from normality. The straight line drawn for reference on the plot is again the line

connecting the 0.25 and 0.75 quantiles of the data. Normal-probability plots highlight the positive skewness in the first half of the MEAF tree-ring series (Figure 2.9).



Histogram with superposed normal PDF. The histogram is a bar chart of frequency or number of observations in various data ranges. A bell-shaped histogram is indicative of normally distributed data. Visual interpretation of the histogram is aided by overplotting a properly scaled theoretical probability distribution for normal distribution with the same mean and variance as the sample series. Such plots for the full-length MEAF tree-ring index clearly emphasize the positive skew of the data relative to normally distributed data (Figure 2.4).

2.4 Lilliefors Test for Normality

The Lilliefors test evaluates the hypothesis that the sample comes from a normal distribution with unspecified mean and variance against the alternative hypothesis that the sample does not come from a normal distribution. The main difference from the well-known Kolmogorov-Smirnov test (K-S test) is in the assumption about the mean and standard deviation of the normal distribution. The K-S test assumes the mean and standard deviation of the population normal distribution are known; the Lilliefors test does not make this assumption. In the analysis of empirical data, more often than not the mean and variance of the population normal distribution are unknown, and must be estimated from the data. Hence the Lilliefors test is generally more relevant than the K-S test.

The Lilliefors test statistic is computed from the maximum vertical offset of the empirical cdf's of (1) the sample, after conversion to Z-scores, and (2) the standard normal distribution. A sample is converted to Z-scores by subtracting the sample mean and dividing by the sample standard deviation, such that the mean of the Z-score series is 0 and the standard deviation is 1.0.

The empirical cdf of this Z-score series is computed. Similarly, the cdf of the standard normal distribution is obtained at the same probability points. The maximum difference of the two cdf's at any point is then computed. Superimposing plots of the two cdf's immediately reveals where the cdf's differ most, and this is the point yielding the Lilliefors statistic.

The Kolmogorov-Smirnov test is identical to the Lilliefors test except that no conversion to Z-scores is made in the K-S test. The Lilliefors test, first presented by Lilliefors (1967), is therefore a modification of the K-S test. To apply the Lilliefors test, you must not just compute the statistic, but test its significance. Exact tables of the quantiles of the test statistic are available; these tables have been computed from random numbers in computer simulations and are stored for reference in Matlab. When you call a function in Matlab to test for normality, the computed value of the Lilliefors test statistic is compared with the internally stored quantiles of the statistic. The following description of the Lilliefors test is from Conover (1980, p. 357).

DATA. Consider a random sample $x_1, x_2 \dots x_n$ of size n , which might be an observed time series. Denote the distribution function of the random variable by $F(x)$. Compute the sample mean, \bar{x} and sample standard deviation, s , and convert the sample to Z-scores:

$$Z_i = \frac{x_i - \bar{x}}{s} \quad i = 1, 2, \dots, n \quad (1)$$

ASSUMPTION: The sample is a random sample. For natural time series, we of course have just the observed sample, and often do not have the luxury of repeating the experiment and drawing repeated samples (running climate history over and over again?). At any rate, we assume the observed series is a random sample. One complication to keep in mind is that with autocorrelated time series (a later topic) the observations are not independent of one another, such that a time series of length n might actually represent fewer than n independent observations.

HYPOTHESES:

H_0 : x_i comes from a normal distribution with unspecified mean and variance

H_1 : x_i does not come from a normal distribution

TEST STATISTIC: The test statistic is the maximum vertical distance between the empirical distribution function of the Z-score series in equation (1) and the distribution function of the standard normal distribution. Plot the cdf of the standard normal distribution and call it $F^*(x)$. Superimpose a plot of the empirical cdf of the Z-scores, and call it $S(x)$. The test statistic is the maximum vertical distance between the two plots, or

$$T_1 = \sup |F^*(x) - S(x)| \quad (2)$$

DECISION RULE: reject H_0 at the significance level α if T_1 exceeds the $1 - \alpha$ quantile in a table of quantiles of the Lilliefors test statistic for normality (e.g., p. 464, in Conover (1980)).

EXAMPLE: Lilliefors test applied to the 1658-1832 portion of the MEAF tree-ring series shows a maximum departure in cdf's at a standardized value of about -0.167 in the tree-ring series (Figure 2.10). From the plot alone, one cannot say whether this departure is significant. Reference must be made to a table based on Monte Carlo simulations. That table indicates the departure is significant ($\alpha < 0.05$), and that the null hypothesis of normality must be rejected. That conclusion is consistent with other graphical evaluations discussed previously.

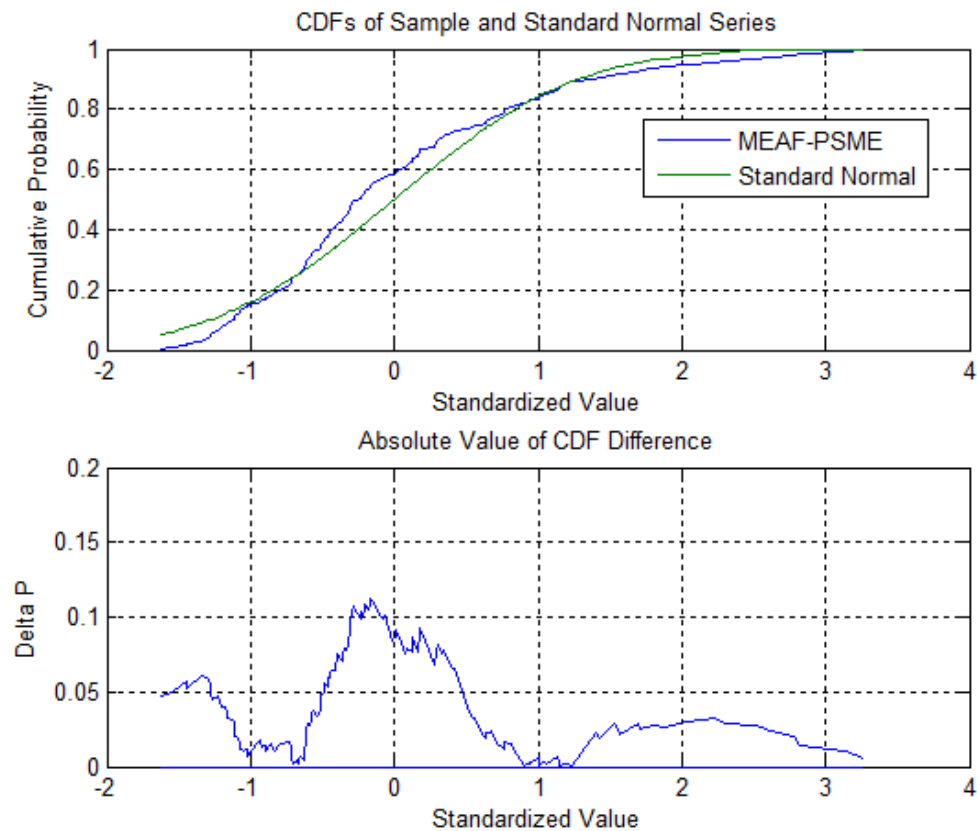


Figure 2.10. Graphical summary of the Lilliefors statistic applied to test for normality of a tree-ring index. Test series is the 1658-1832 portion of MEAF tree-ring series. (Top) Empirical cdf's of a standard normal series and of the Z-scores of the tree-ring series. (Bottom) Difference between the two cdf's as a function of the standardized value of the tree-ring series. This absolute difference is labeled "Delta P". The maximum absolute value of Delta P is defined as the Lilliefors statistic. For these data, the Lilliefors statistic is large enough to be significant ($\alpha < .05$) such that the hypothesis of normality is rejected.

2.5 Matlab

The Matlab Statistics Toolbox has functions for statistics and plots used in this chapter. The function are defined and described in the Matlab help.

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