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The Varve Interpolation Program 3.0.0 - A unique and easy to use tool for incompletely varved sediments

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ABSTRACT

Annually laminated (varved) sediments are particularly interesting for palaeo-environmental reconstruction, since they allow independent, high resolution chronological control. But often varved archives contain intervals in which seasonal layers did not form every year. To construct independent varve chronologies from such archives varve interpolation is required. Here, a significantly advanced Varve Interpolation Program (VIP) is presented, which uses a novel approach to interpolate varves. Through probability distribution fitting the varve thickness frequency distribution of an interval is approximated and used for interpolation. The new approach is superior in many respects to the approach used in the original VIP 1.0.0, but retains all the advantages, such as objectivity, reproducibility and the fact that it does not rely on well varved intervals. The program is designed for common log-normally distributed varve thickness frequency distributions. It is realised in Matlab, but comes with a graphical user interface, which allows easy handling and requires no prior knowledge about Matlab. The program can be run fully automated, but also allows manual control of settings. While the accuracy of the results depends on the characteristics of the data and the degree of varve formation/preservation, the application examples presented here show that under suitable conditions accuracies in the range of 2% can be achieved.

1. Introduction

Varved sediments are extremely useful archives for palaeo-environmental reconstruction, since they enable the construction of independent chronologies with high accuracy and precision. At the same time they can offer a wealth of different proxies to exploit for palaeo-environmental reconstruction, such as microfacies, pollen, diatoms, biomarkers, geochemistry and more (e.g. Ojala et al., 2008; Kossler et al., 2011; Rach et al., 2014). However, continuously varved archives are rare and often a varved sediment profile contains intervals in which varve formation or preservation is incomplete (e.g. Hughen et al., 2004; Lauterbach et al., 2011; Corella et al., 2016). To construct independent varve chronologies from such archives, interpolation is required. Previously, we presented a new approach to varve interpolation (Schlolaut et al., 2012), which used count distance frequency (CDF) distributions to estimate mean sedimentation rates, which were used to interpolate an incompletely varved record. The approach was realised as a program in Matlab (Varve Interpolation Program (VIP) version 1.0.0). While the program produced robust results (Marshall et al., 2012; Schlolaut et al., 2012) it also has a number of weaknesses. For instance, it uses artificial data to determine certain variables for interpolation. The parameters for the artificial data need to be determined manually, which introduces a degree of subjectivity if not error. Another example for a weakness is the limited application range since archives should ideally have a smaller annual sediment accumulation variability than 1.5 times the mean sedimentation rate (SR). This means that the value of sediment accumulation in a certain year (in mm) should not be higher than the value of 1.5 times the mean SR (in mm/yr) of the interval it lies in. Furthermore, the VIP 1.0.0 was not particularly user friendly and somewhat complicated to apply. However, the successful application of the program to the Lake Suigetsu chronology (Bronk Ramsey et al., 2012) demonstrated its potential, which motivated the further development of the program.

Here, the advanced VIP 3.0.0 is presented, which uses a novel approach for interpolation. It is superior to VIP 1.0.0 in almost every regard, from usability over application range to the accuracy of the results.

CDF (count distance frequency) data lie at the heart of the old and new VIP. In the case of a completely varved archive the count distance values are the same as varve thickness values. But when seasonal layers did not form every year, the count distances represent annual sediment accumulation as well as multiples of it. The new VIP 3.0.0 uses

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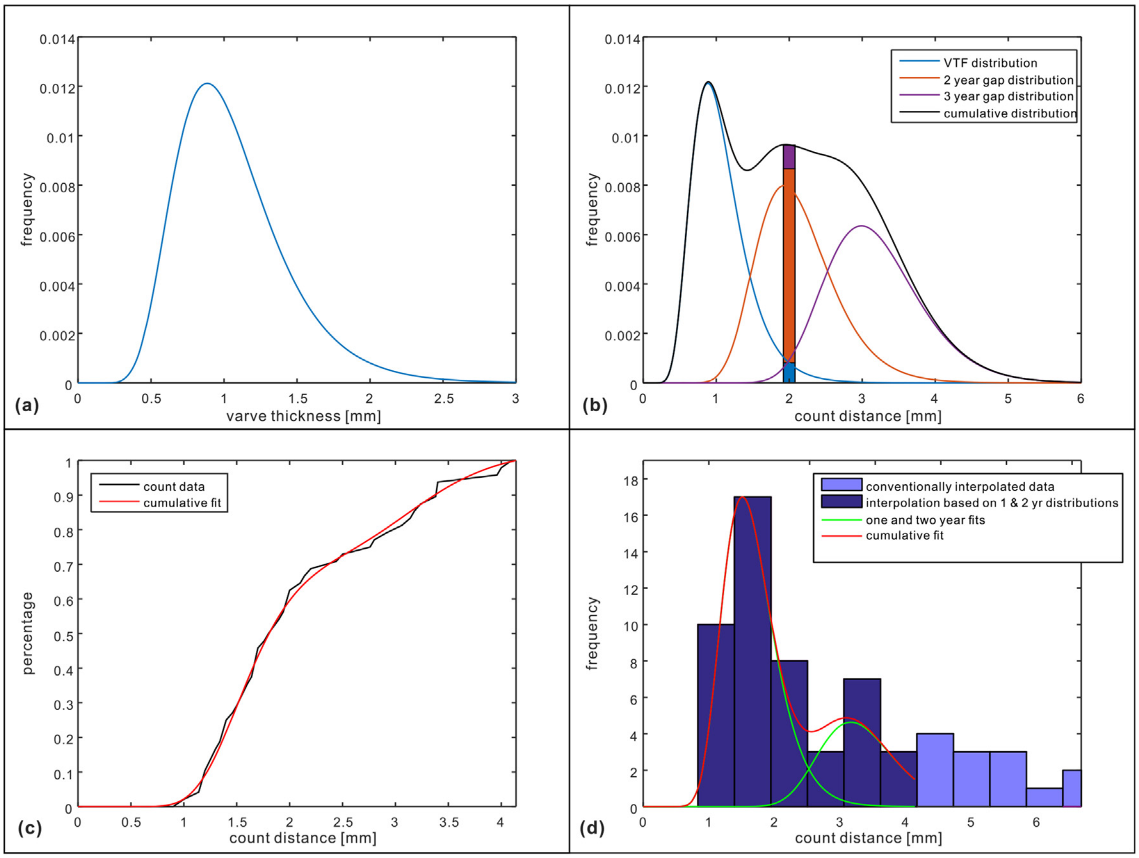

Fig. 1. (a) Theoretical log-normal varve thickness frequency (VTF) distribution, **(b)** count distance frequency (CDF) distribution (black) of a theoretical count in which counts are one (blue), two (orange) and three (purple) years apart; the bar shows how many of the counts around a count distance of 2 mm are one, two and three years apart, **(c)** fitting of a theoretical CDF distribution (red) based on counts that are one and two years apart to measured data (black) and **(d)** approximated visualisation of the fitting in which the highest frequency value of the theoretical distribution is set to be equal the highest frequency value of the bar plot; **(c)** and **(d)** are using the same data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

probability distribution fitting to directly estimate the varve thickness frequency (VTF) distribution from a CDF distribution. The estimated VTF distribution is then used for interpolation.

In the following section the fundamental *modus operandi* of the program is explained. This is followed by a more detailed description of aspects particularly important for the application of the program. Application examples are provided at the end of this paper to illustrate strengths and weaknesses of the VIP 3.0.0 and to give readers a better understanding of the application range of the program. The program itself comes with a manual explaining the settings, data structure requirements et cetera.

2. The VIP 3.0.0 in a nutshell

For the program we assume that the varve thickness frequency (VTF) distribution of an archive can be represented by a logarithmic normal distribution (Fig. 1a):

$$p_1(x_{1\ldots N}) = \frac{1}{\sqrt{2\pi}\sigma x}e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} \quad x_1 = 0, \quad \Delta x = const. \tag{1}$$

with p being the probability of a certain varve thickness, x being discrete count distances/varve thicknesses, μ being the mean and σ the standard deviation. From experience, this assumption should be true for many, though not all, archives. For instance, a lake which experiences irregular, massive algal blooms in certain years may actually show more of a bi-modal VTF distribution, such as Lake Challa (Wolff et al., 2014), in which case the VIP is not applicable.

An archive which has a log-normal VTF distribution, but in which seasonal layers did not form every year, will contain count distance values which represent double the annual sediment accumulation, i.e. these counts are two years apart. These count distances will follow a distribution which can be expressed by the following equation in dependence of equation (1):

$$p_2(x_i) = \begin{cases} \sum_{k=0}^{i-1} p_1(x_{i-k})\, p_1(x_{1+k}), & i \le N \\ \sum_{k=i-N}^{N-1} p_1(x_{i-k})\, p_1(x_{1+k}), & i > N \end{cases} \tag{2}$$

The two distributions represented by equations (1) and (2) are illustrated in Fig. 1b. Adding them up produces the count distance frequency (CDF) distribution an archive would have, which contains only seasonal layers that are either one or two years apart. The concept can be extended for seasonal layers three, four or more years apart (Fig. 1b).

The VIP 3.0.0 approximates the measured CDF distribution of an archive using the combined distribution from equations (1) and (2) using a Monte Carlo approach, varying σ and a scaling factor for equation (2). To reduce calculation time μ is not varied but the mode position (x_{mode}) of the CDF distribution is determined, which equals x_{mode} of the VTF distribution (if one year count distances dominate), i.e. x_{mode} of the distribution from equation (1). The relation

$$\mu = \ln(x_{mode}) + \sigma^2 \tag{3}$$

is then used to determine μ in dependence of σ and x_{mode}. The combined distributions of (1) and (2) which give the best fit with the measured CDF data (Fig. 1c and d) can then directly be used for interpolation. As illustrated in Fig. 1b, the distributions from equations (1) and (2) show the percentage of counts which are one year and the percentage of counts which are two years apart for any count distance value. In