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A time-series analysis software package (*Acycle*) for paleoclimate research and education



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1. Highlights

- We develop a software package for cyclostratigraphic research and education
- Many of the functions are powerful and specific to astrochronology
- It includes models of sedimentary noise and variable sedimentation rate estimation
- It is easy to use with a fully implemented graphical user interface (GUI)
- *Acycle* is open-source and available free of charge

2. Introduction

Three reasons motivated development of the *Acycle* time series analysis program.

(1) to broaden and encourage the experience of time series analysis

(2) to speed the process for time-consuming iterative procedures

(3) to provide objective methods for astrochronology as reproducibility becomes a major challenge

This software package* integrates visualization and analysis of time-series and printing graphics using the MATLAB programming language.

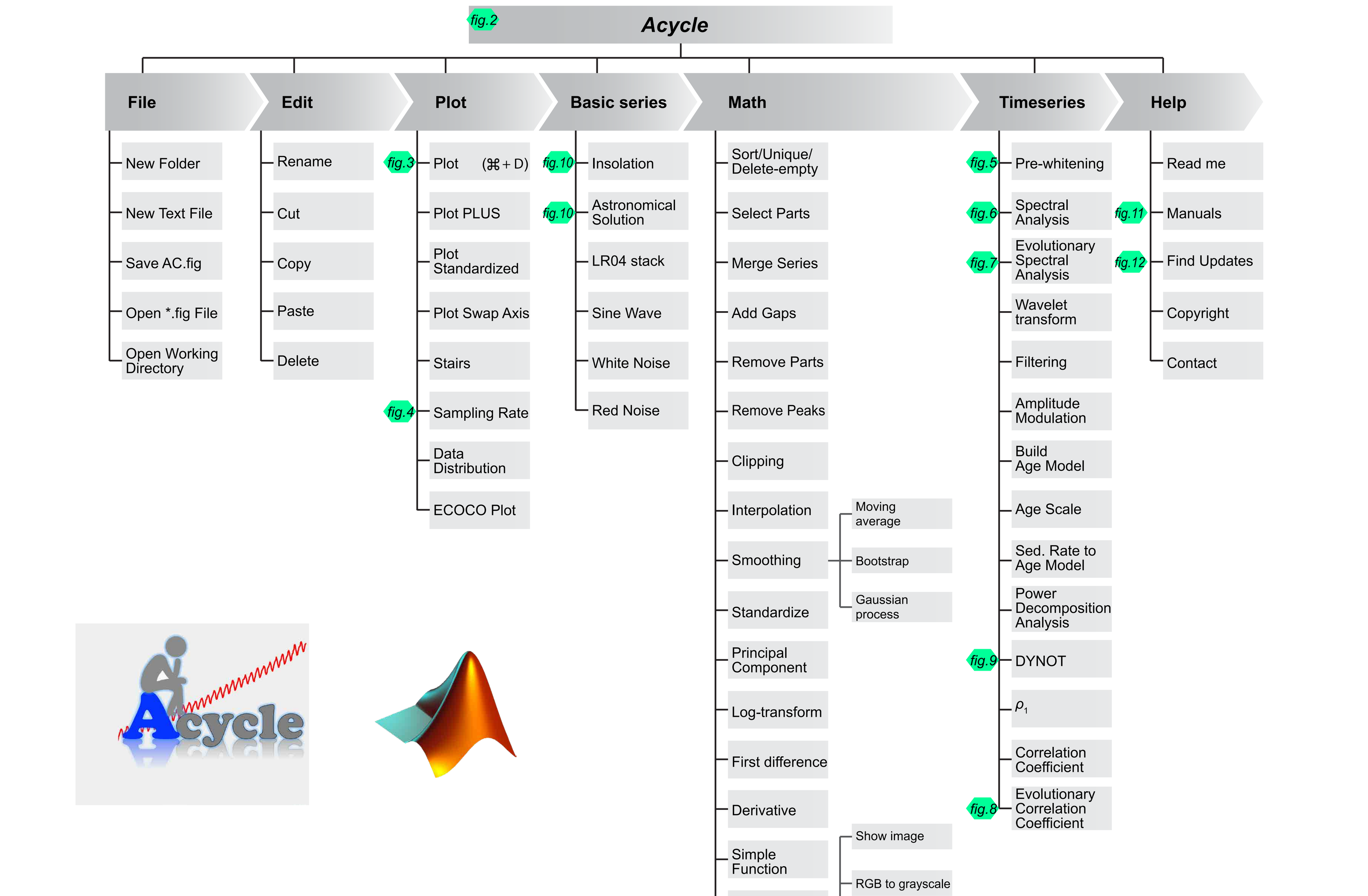

Figure 1. *Acycle* components.

3. The demonstration time series

The paleoclimate time series used to demonstrate *Acycle* is the XRF generated iron (Fe) content of Core BH9/05 from the Paleogene Central Basin of Spitsbergen, Svalbard. The full iron series of the Paleocene-Eocene Frysjaodden Formation was studied for the construction of an astrochronology for the global carbon cycle perturbation associated with the Paleocene-Eocene thermal maximum (PETM) (Cui et al., 2011).

☆ There is no specific requirement for hardware. Operating systems include Windows XP or later and Mac OS X 10.6 or later. This software is developed in MATLAB version 2015b. MATLAB is essential for the MATLAB version of the *Acycle* package. The size of *Acycle* is 47.5 M.

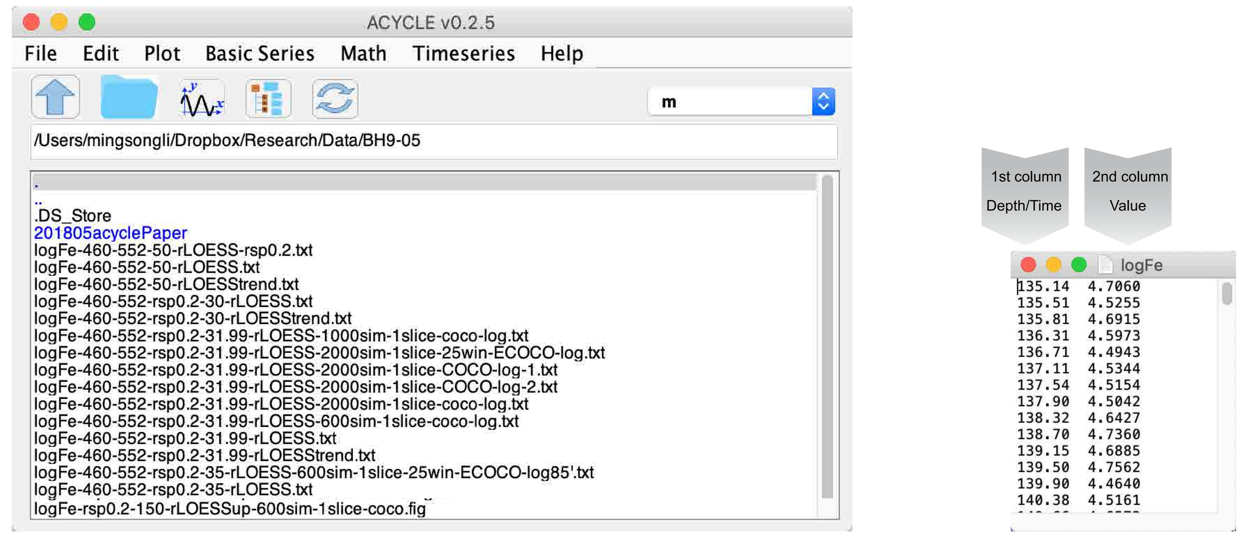

Figure 2. The *Acycle*. Left panel: GUI (see Fig. 4 for more details). Right panel: the data file format.

3.1. Data preparation

Acycle includes several toolboxes to facilitate the data preparation processes. The program allows users to sort data in ascending or descending order. Two or more values for the same time (or depth) may be averaged with the "Unique" function. Other useful tools include the moving average function and a first-difference function (Fig. 1).

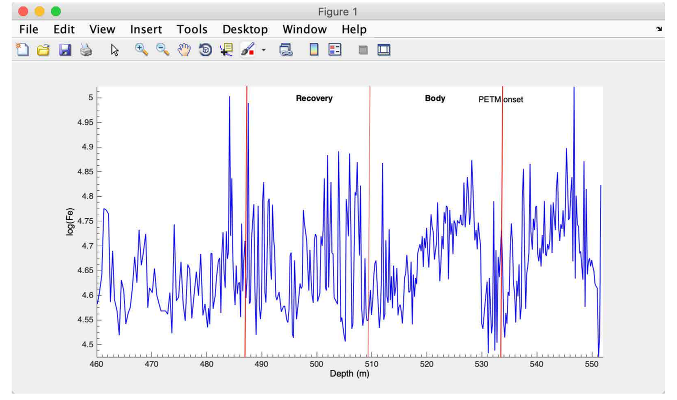

Figure 3. Log-transformed Fe paleoclimate series from 552 m to 460 m at Core BH9/05 in the Paleocene Central Basin of Svalbard. The Fe series is shown with PETM event onset and "body" interval of a prominent negative carbon isotope excursion, followed by a gradual recovery stages (Cui et al., 2011).

3.2 Sampling rate and interpolation

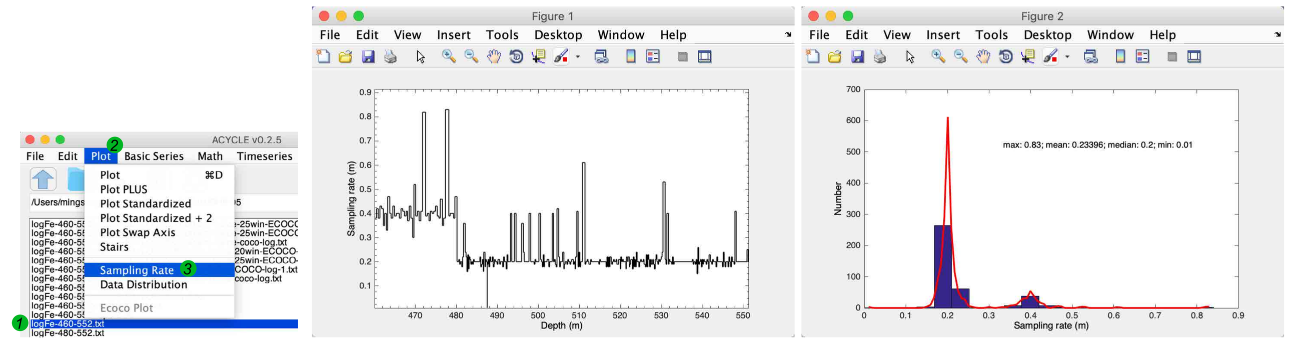

Figure 4. Left panel: *Acycle* GUI. Middle panel: Sampling rate of the Log(Fe) series at Core BH9/05 in the Paleocene Central Basin of Svalbard. Right panel: Histogram and the "kernel" fit of the sampling rates. Two peaks are centered at 0.2 and 0.4, respectively. These plots are generated using the "Sampling Rate" function in the "Plot" menu (Fig. 1).

3.3 Prewhitening

The log(Fe) series were pre-whitened using "Pre-whitening" function by subtracting a long-term trend.

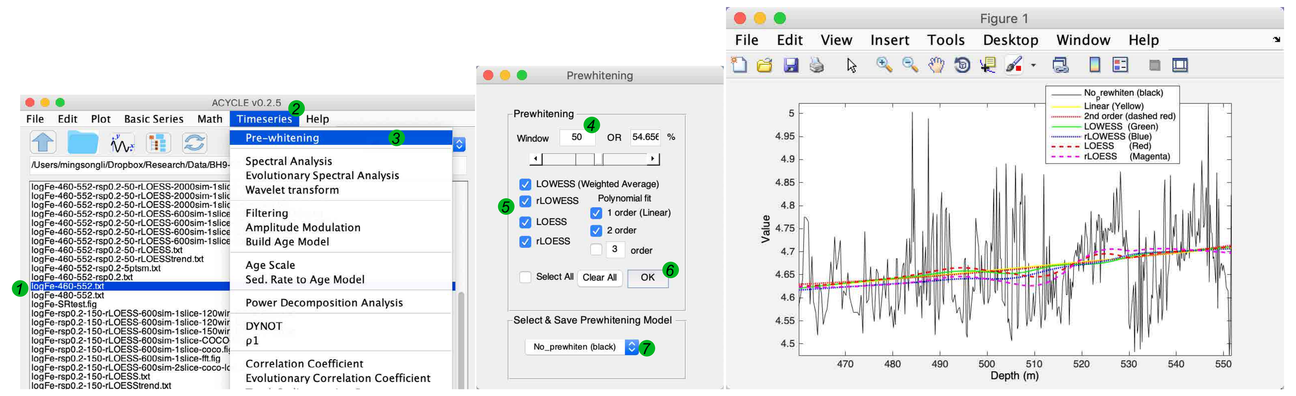

Figure 5. Left panel: *Acycle* GUI. Middle panel: The "Prewhitening" GUI. Right panel: The log(Fe) series at Core BH9/05 is shown with the linear trend, second order polynomial fit, and various 50-m secular trend using MatLab's "lowess", "rlowess", "loess", and "rloess" methods.

3.4 Power spectral analysis

Power spectra of the Log(Fe) series were examined for frequency peaks using the "Spectral Analysis" function.

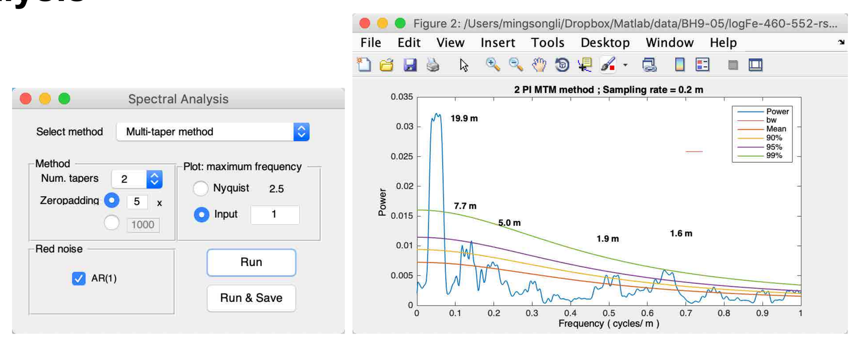

Figure 6. Left panel: The "Spectral Analysis" GUI. Right panel: 2π multitaper (MTM) power spectral analysis of the Log(Fe) series at Core BH9/05 after removing the 50 m "rloess" trend and interpolation of 0.2 m sampling rate. Cycle wavelengths are marked at top of the peaks. bw: bandwidth.

3.5. Evolutionary power spectral analysis

Evolutionary fast Fourier transform (FFT) spectrograms for inspecting stratigraphic frequencies and trends of the time series were computed using the "Evolutionary Spectral Analysis" function.

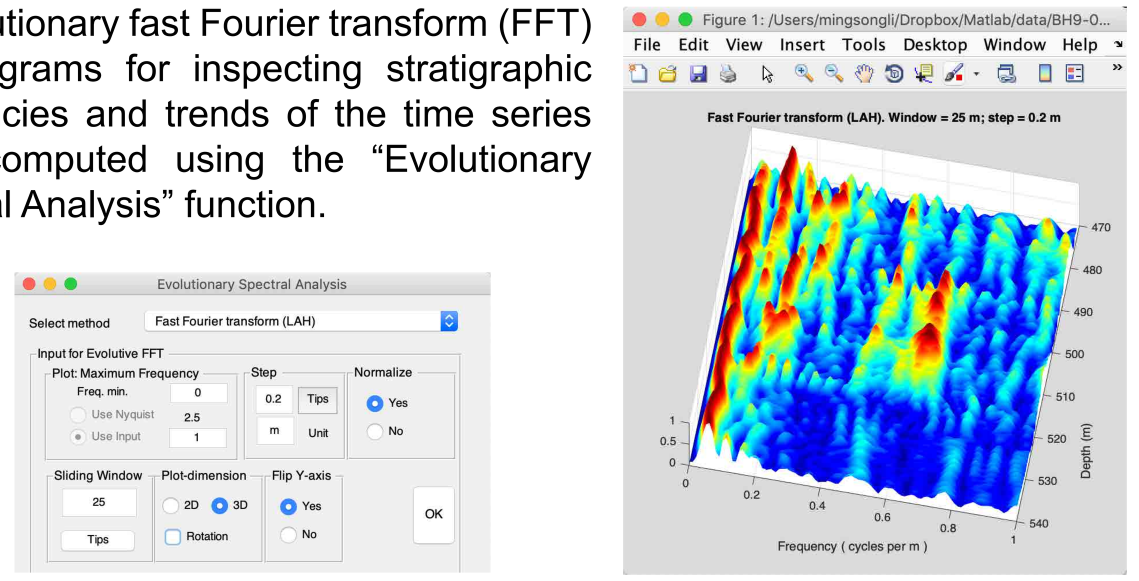

Figure 7. Left panel: Evolutionary Power Spectral Analysis GUI. Right panel: 3D evolutionary FFT spectrum of the log(Fe) series after removing 50 m "rloess" trend using a running window length of 25 m and a sliding step of 0.2 m.

3.6 Evolutionary correlation coefficient (ECOCO)

ECOCO (Li et al., 2018 *EPSL*) was calculated to track variable sedimentation rate and test astronomical origin of stratigraphic oscillations.

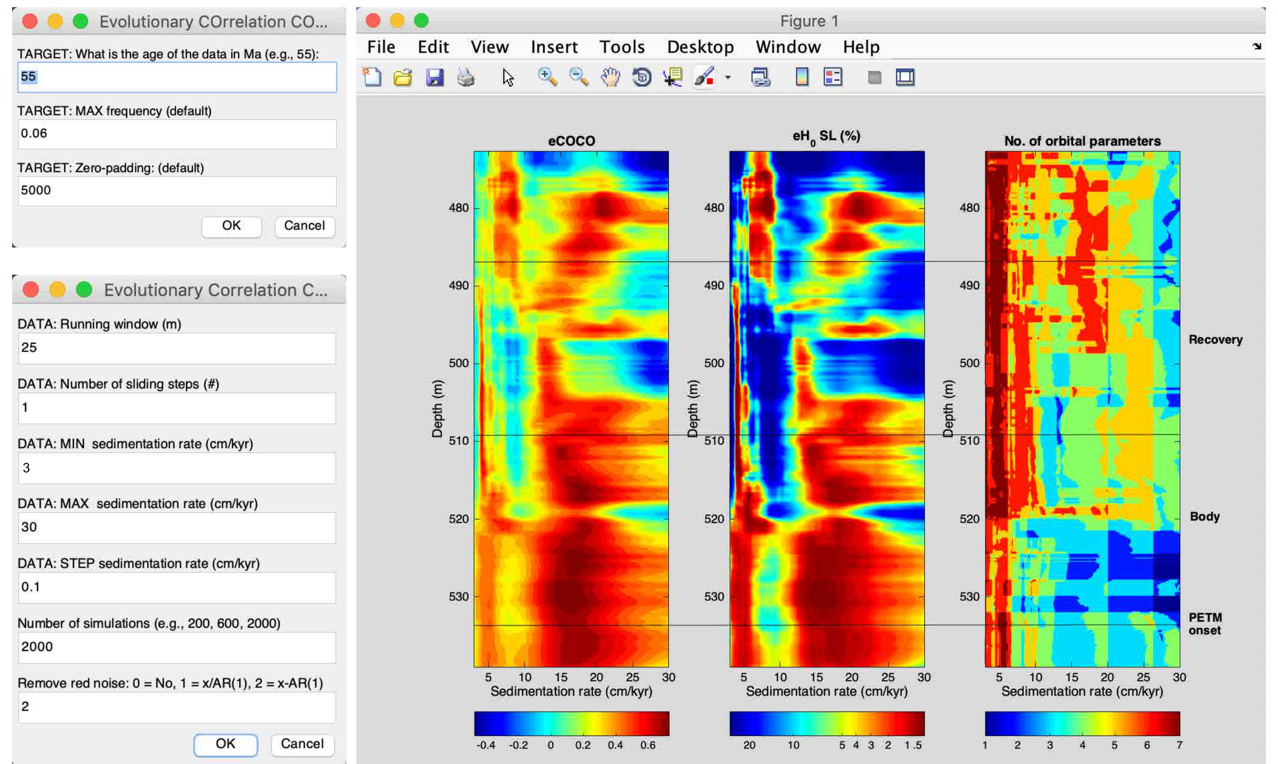

Figure 8. eCOCO GUI and eCOCO results of the Fe series at Core BH9/05. Left panel: Evolutionary correlation coefficient. Middle panel: Evolutionary H_0 significance level. Right panel: Evolutionary number of contributing astronomical parameters. The sliding window size is 25 m; the sliding window step is 0.2 m. All periodogram removes the AR(1) red noise model. The number of Monte Carlo simulations is 2000. Sedimentation rates range from 3 to 30 cm/kyr with a step of 0.1 cm/kyr.

3.7 Sedimentary noise model

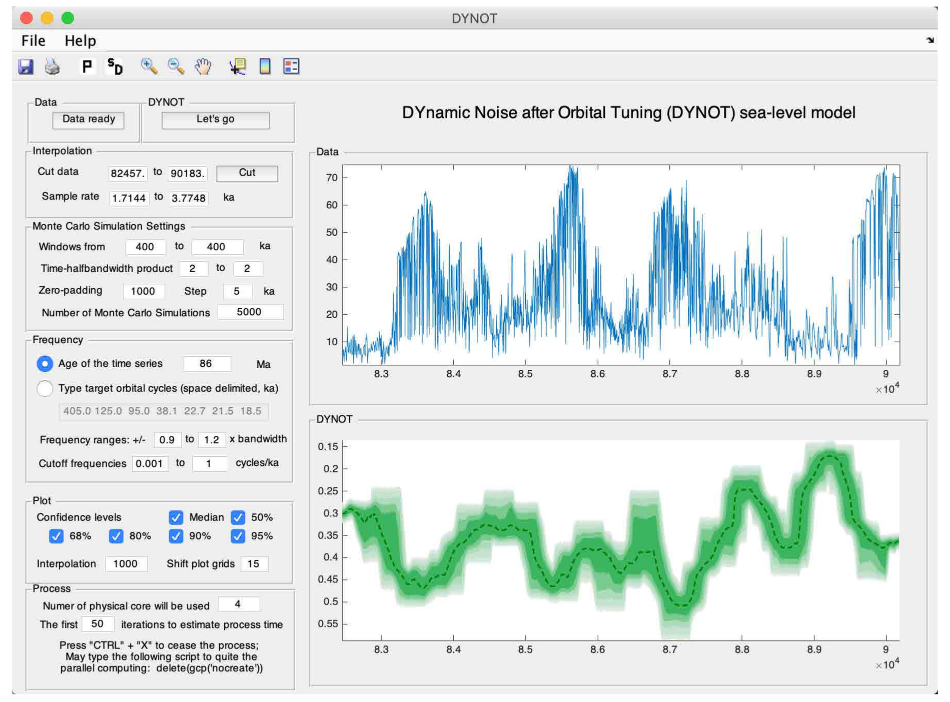

Figure 9. DYNOT GUI. (Data not discussed.)

A sedimentary noise model has been recently developed for the reconstruction of past sea-level changes from astronomically forced marginal marine stratigraphy (Li et al., 2018 *Nature Commun.*). The noise model includes two complementary approaches: lag-1 autocorrelation coefficient (ρ_1) and dynamic noise after orbital tuning (DYNOT). Both approaches are included in *Acycle*.

4. Toolboxes and supporting documents

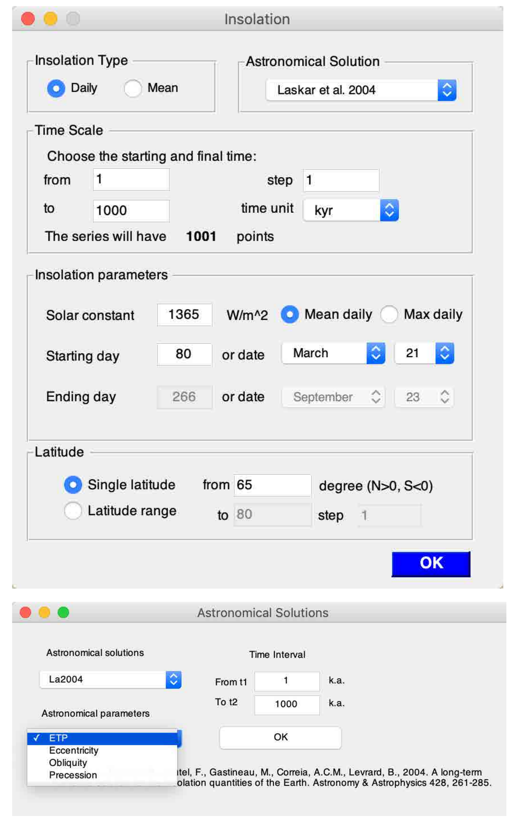

Figure 10. Solar insolation calculator (top panel) and a toolbox generating astronomical solutions (bottom panel).

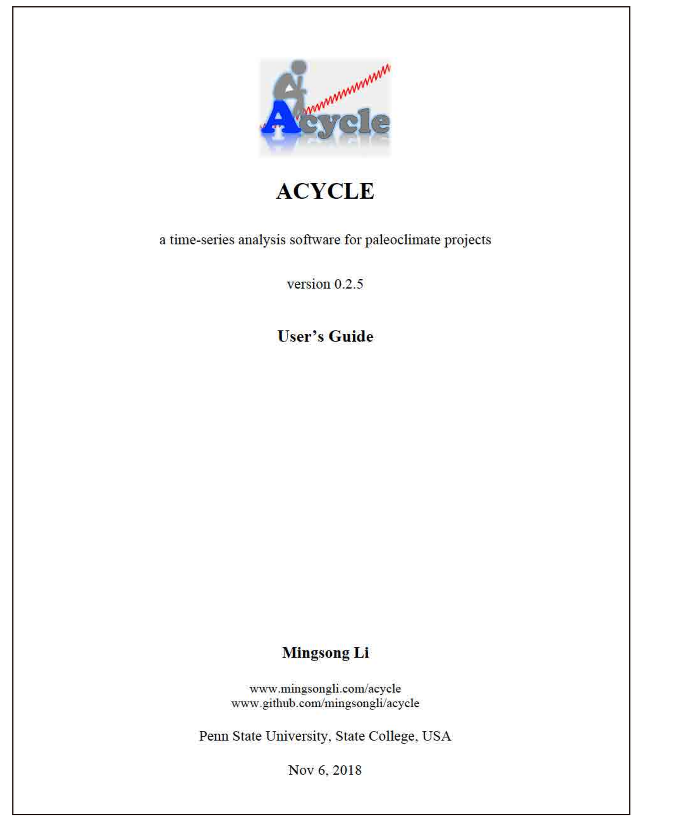

Figure 11. *Acycle* User's Guide.
https://github.com/mingsongli/acycle/blob/master/doc/AC_User's_Guide.pdf

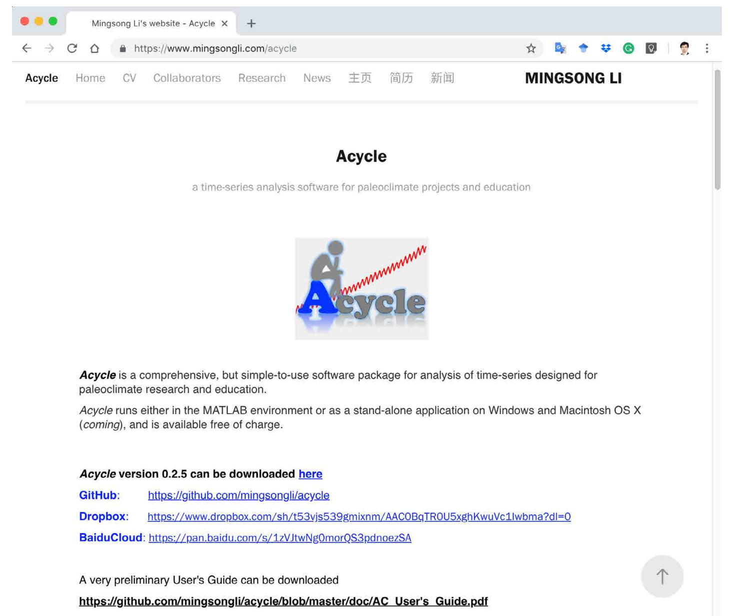

Figure 12. Website for *Acycle*.

Website for *Acycle*:
mingsongli.com/acycle

Link to the code:
github.com/mingsongli/acycle