Numerical simulations of the effects of astronomical forcing on nutrient supply and oxygen levels during the Devonian

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Devonian, anoxia and Milankovitch

The Devonian stage, spanning sixty million years, witnessed at least 29 identified anoxic events (Becker et al., 2020). These events were predominantly characterized by the deposition of black shales and associated with carbon isotopic excursions. It has been postulated that concurrent trends in CO_2 and silicate weathering during the Devonian period created conditions conducive to ocean anoxia. Moreover, there is mounting evidence to suggest that the periodic recurrence of these events in sedimentary records may have been influenced by astronomical forcing, such as changes in Earth's axis rotation and orbit geometry (De Vleeschouwer et al., 2017; Da Silva et al. 2020). Additionally, it has been observed that the Annulata, Dasberg and Hangenberg anoxic Devonian black shales in Poland are separated by approximately 2.4 million years - the expected distance between two eccentricity nodes - yet without a clear phase relationship (anoxia may be associated with either a maximum or a minimum).

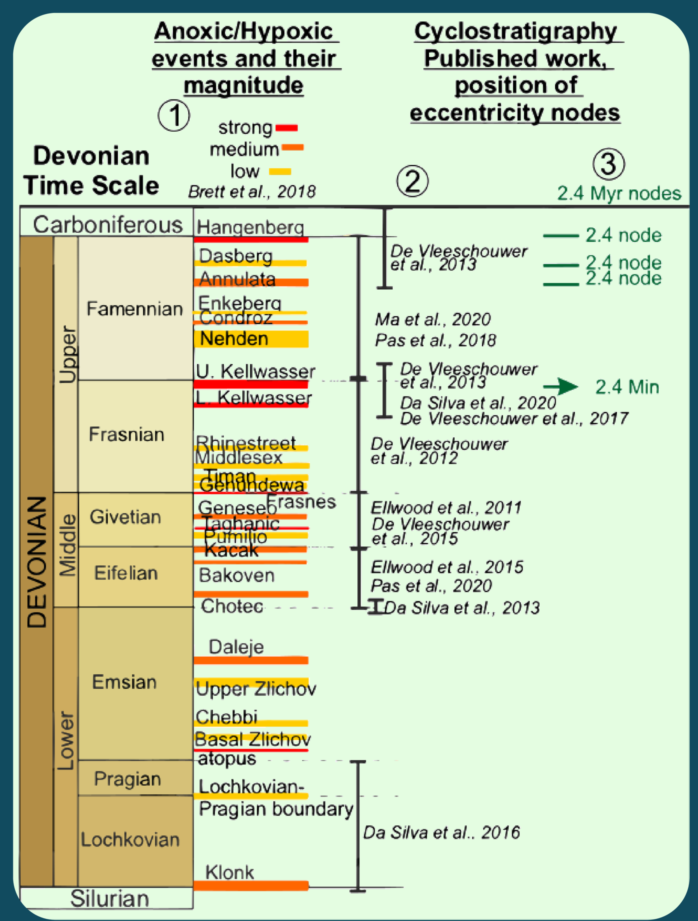


Fig. 1: Devonian time frame and the Anoxic/Hypoxic events (1) associated with published cyclostratigraphy studies (2, black bars, with corresponding references) and the positions of 2.4-Myr long eccentricity cycle nodes (3). The four identified 2.4-Myr nodes are all associated with important anoxic events.

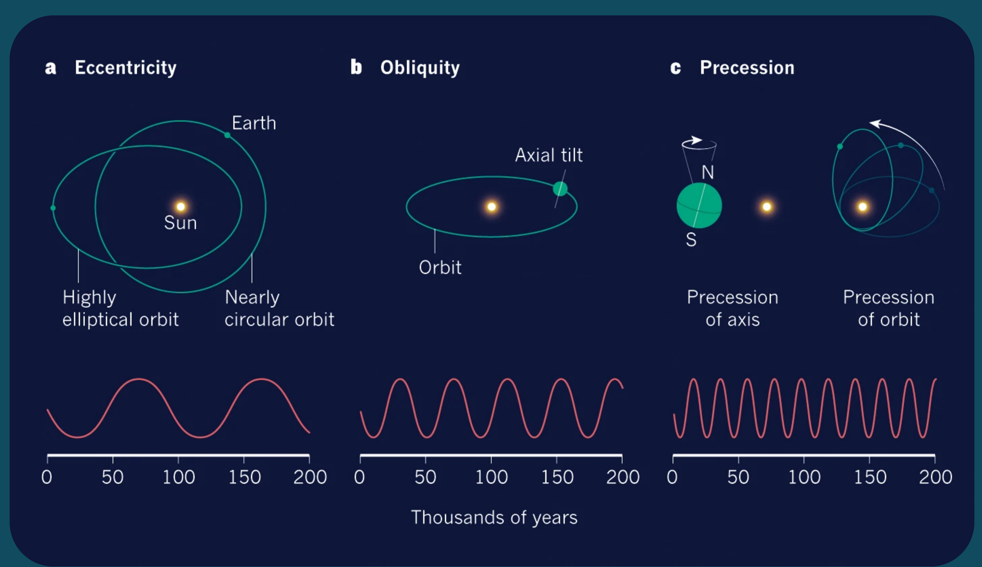


Fig. 2: Milankovitch Cycles, *Maslin, M. Forty years of linking orbits to ice ages. Nature 540, 208–209 (2016).*

$$e\sin\varpi = \sum_i P_i \sin(\alpha_i t + \eta_i)$$

$$\varepsilon = \varepsilon^* + \sum_i A_i \cos(\gamma_i t + \zeta_i)$$

$$e = e^* + \sum_i E_i \cos(\lambda_i t + \phi_i)$$

a. Eccentricity refers to the shape of the Earth's orbit around the Sun. It varies between nearly circular and slightly elliptical over time. This variation affects the distance between Earth and the Sun. Changes in eccentricity slightly affect the total amount of insolation received over the year, but its most important consequence for climate is to modulate the effect of precession. It varies along different cycles of ~100 ky, 400 ky and 2.4 My.

b. Obliquity refers to the tilt of the Earth's axis relative to its orbit around the Sun. It changes over time and affects the distribution of solar radiation across latitudes, in annual mean. The seasonal contrast also increases when obliquity increases. The cycle is ~41ky.

c. Precession refers to the revolution of the position of the perihelion (closest point of Earth's orbit to the Sun), with respect to the position of the equinoxes. This influences the amount of solar radiation received at any given month, and therefore affects the seasonal contrast. The cycle is ~21 ky today but was shorter during the Devonian, estimated to ~19 ky.

Workflow and model chain

A Global Circulation Model (GCM) is employed in the generation of equilibrium climatologies. Although this task represents the most significant computational expense in the process, it necessitates execution only once

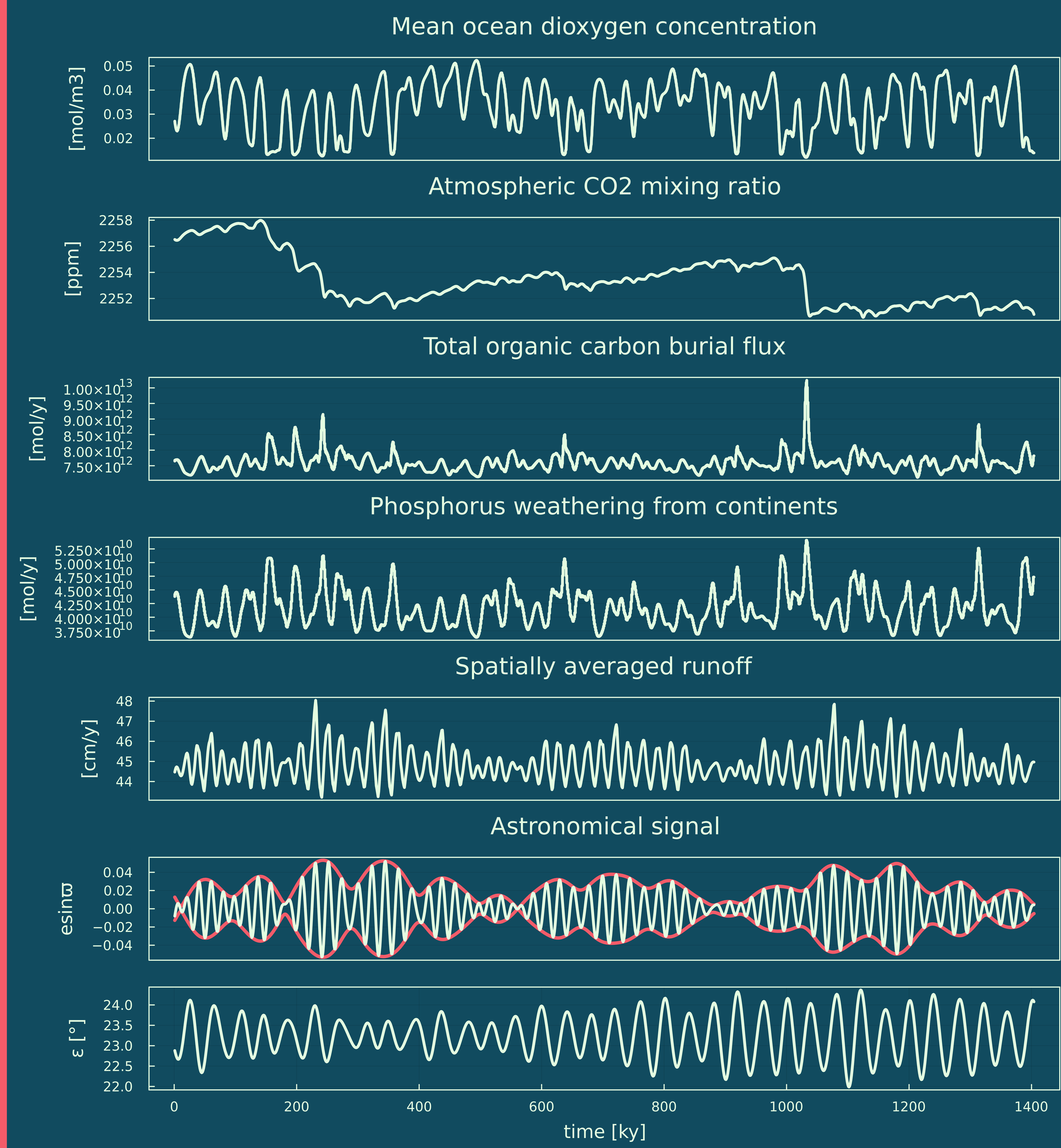
Subsequent to the generation of runoff and surface temperature fields, a Gaussian Process emulator (Lord et al., 2017) is employed for training purposes. This statistical approach confers the advantage of providing both an output and an associated error bar.

$$f(x) \sim \mathcal{GP}(\mu, k)$$

Given an astronomical scenario specified by a time series of three parameters, the output takes the form of three-dimensional grids that faithfully mirror the changes in climatologies resulting from variations in the Earth's orbit.

The scenarios are ultimately incorporated into a modified iteration of GEOCLIM (Maffre et al., 2021), a collection of models of intermediate complexity that calculate the geochemical cycles of several species, such as carbon and oxygen, over geological timescales.

An output example...



Utilizing 27 experiments and a CO_2 concentration of 2180 ppm, in conjunction with the time variation of the three astronomical parameters taken from a section of Laskar et al., 2004, we have generated time series data for several geochemical species relevant to the study of Ocean Anoxic Events. Notably, our data reveals a peak in organic carbon burial flux that may result in the deposition of black shales on the ocean floor.