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Statistical emulation of the rapid response of a climate model to astronomical forcing variations

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We are interested in the response of a general circulation model of the atmosphere and the ocean to variations of the astronomical forcing during the Pleistocene. However, the demand on computing resources would be far too excessive for long time simulations. So, our aim is to formulate a reduced order model for this response, by the construction of a statistical model called an emulator, trained on the available runs.

Insolation during long time variations is influenced by the eccentricity e, the longitude of the perihelion ϖ and the obliquity ε. To deal with this astronomical theory of paleoclimate, input data are expressed in an adequate form and then consider the base $(\varepsilon, e \cdot \sin(\varpi), e \cdot \cos(\varpi))$.

The choice of a small number of experiments to develop the emulator is crucial. The distribution of the experimental points was made following two plans in order to compare them. A full factorial design and a Latin hypercube one. The latest maximize the minimum distance between the design points. 27 experiments by plan were then made.

Here, we have developed and designed an emulator of a three-dimensional Earth system model of intermediate complexity (LOVECLIM, Goosse et al., 2010), considering the principal components of its response (surface temperature) using a weighted principal component analysis. The first three principal component account for 99% of the response variance.

The emulator proposed here is based on a Gaussian process model. This is a stochastic process for which any finite set of the simulated data has a joint multivariate Gaussian distribution (Rasmussen, 1996). We further consider the combination of the Gaussian process with a linear regressor on the one hand, and with a quadratic one on the other hand. Statistical methods of model selection are used to choose the appropriate emulator, such as the leave-one-out cross-validation, that is, using a single data point in the training set for prediction.

The Gaussian process emulator provides the quantification of uncertainty about evaluating the emulator at a limited number of input data. The surface responses obtained for each emulator parameter allow us, considering the uncertainties, to study the influence of the astronomical parameters variations on the output, and to detect of non-linearities.