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Extended Abstract

Sensitivity and uncertainty analyses in climate research: Tool development and application for an atmosphere model

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In climate and climate impact research model development and application are important methodologies. Numerical models of the Earth system and its subsystems play a key role in understanding the physical processes and in assessing implications of future climate change. Typically, such models are characterized by a high complexity of nonlinear processes with threshold effects and strong interactions, an intrinsic variability of processes, a large number of uncertain model factors, and large volume of multi-variate and multi-dimensional output. In recent years, there has been a growing demand for complementing the findings from simulation experiments with sensitivity and uncertainty measures and to share such information with the scientific community as well as with policy and decision makers (e.g., Katz et al. 2013 and IPCC 2014).

Typically, such simulation models are implemented in programming languages rather than modelling systems. Beside validation tasks, simulation experiments are mainly performed for scenario and re-analyses. For simulation studies with the focus on sensitivity and uncertainty analyses (SUA) methodical challenges arise from interfacing the model to appropriate tools, experiments for sensitivity and uncertainty analyses (SUA) in high-dimensional factor spaces, load distribution of the run ensemble, specification of experiment-specific measures during experiment analysis, and visual analytics of experiment output and derived SUA measures.

SimEnv (Flechsig *et al.* 2013) presented in this paper, is a multi-run simulation environment for SUA of multi input / output models that meets most of the above criteria: Experiment design is based on pre-defined deterministic, probabilistic and Bayesian experiment types for factor spaces of any dimension that only have to be equipped with numerical information. Experiments cover variance based and Monte Carlo techniques, local and qualitative sensitivity analysis, (fractional) factorial designs, Bayesian calibration, and one-criterial optimization.

The simulation environment comes with a simple model interface that requires only minimal source code modifications of C/C++, Fortran, Java, Python, Matlab, Mathematica, GAMS or shell script models. Multi-variate / -dimensional experiment output is stored in self-describing NetCDF data format. The environment allows for flexible load distribution strategies of the single runs from the run ensemble, supporting multi-core processor machines and compute clusters. In experiment analysis, chains of built-in and user-defined operators are applied to multi-dimensional experiment output over the factor space, to external (reference) data, and to other SimEnv experiments to derive SUA measures from secondary experiment output.

SimEnv is coupled to the visualization system SimEnvVis (Nocke 2007) for interactive explorative visual data analysis. It exploits metadata from experiment design and analysis to select appropriate visualization techniques. One of the advantages of SimEnvVis is the ability to cope with multi-run datasets by special visualization techniques like parallel coordinates and graphical tables.

SimEnv has been used for modelling studies with different objectives (e.g., Knopf et al. 2006 and 2008, and van Oijen et al. 2013). Here, we applied it to study the atmosphere model Aeolus (Coumou et al. 2011). Aeolus is a statistical-dynamical atmospheric model based on time-averaged equations, and therefore much faster than the more widely used atmospheric general circulations models. With Aeolus it is possible to run climate simulations up to multi-millennia timescales and its computational efficiency enables experiment settings with high computational costs in terms of number of runs.

In a first step, we applied simulated annealing technique to optimally tune the models representation of the Hadley cells as well as wind velocities to available observational data. Next, we studied the sensitivity of large-scale atmospheric circulation patterns to different forcing patterns. In particular, we were interested in quantifying the sensitivity of the Hadley circulation to the key dynamical forcings involved and the likely causes behind the observed strengthening and widening of the Hadley cell in recent decades. With appropriate methods we investigated the impact of additional parameters to the Hadley cell's strength and position. Afterwards, we identified and examined in a two-level approach the most sensitive parameters of Aeolus to the Hadley cell's dynamics. For all settings we applied visual data analysis in the coupled multi-dimensional factor – state space.

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