A Discourse About Quasi-realistic Climate Models and Their Applications in Paleoclimatic Studies

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Summary. The role and application of quasi-realistic climate models in paleoclimatic studies is reviewed. Conceptual aspects of modelling, such as the validation of positive analogs and the application of neutral analogs, are discussed. The mathematical basis of quasi-realistic models and the major modes of applications are presented. An extended 'control run' and a transient simulation of the *Late Maunder Minimum episode* (1675-1710) are used as a demonstration of the general ideas.

1 Introduction

When referring to models, a large variety of different concepts are meant, ranging from simple analogs like maps, to idealizations, conceptualizations, huge miniaturizations and, in particular in climate science, to a mathematically constructed substitute reality [29]. In the following an attempt is made to review the use of models in the field of paleoclimatic reconstructions. We deal with

- Conceptual aspects of modelling (Sect. 2)
- Quasi-realistic climate models ('surrogate reality') (Sect. 3)
- Equilibrium, transient and data-driven model simulations for reconstruction of historical and paleoclimate (Sect. 4)

2 Conceptual Aspects of Climate Modelling

2.1 General Aspects of Environmental Modelling

Here, we follow the modelling concept suggested by Hesse [14] according to which reality and model have attributes, some of which are known to be shared (positive analogs), while others are unknown if they are common to reality and model (neutral analogs).

In fact, ‘models’ are to some extent like children’s toy models - namely a simplified composition, which replicates some features of the original. In the case of a child’s toy train, the model moves on tracks, wagons are coupled together and drawn by a locomotive and the like. When colliding, both model and real trains tend to derail (Fig. 1).

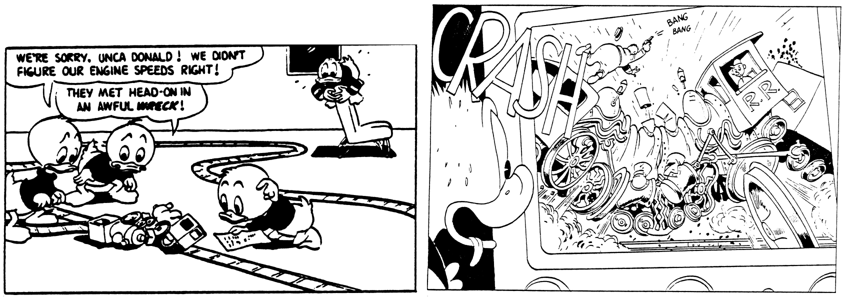

Fig. 1. Toy train as a model. A positive analog of the toy train with real trains model is determined: A severe accident is taking place when both toy or real trains are colliding. From Barks, C., 1954: The Runaway Train. Walt Disney’s Comics and Stories 195

In Hesse’s terminology, these are positive analogs. Other real world features are not available in the model; for example, in the example of the toy train, the engines is not driven by steam but by a mechanical clockwork. These are negative analogs. Are there neutral analogs? Maybe not for an adult, but for children there are plenty. In the example of Fig. 2, the expected timing and the location of the collision of two trains is estimated from an experiment with the toy trains, and adequate measures to mitigate the impact are taken.

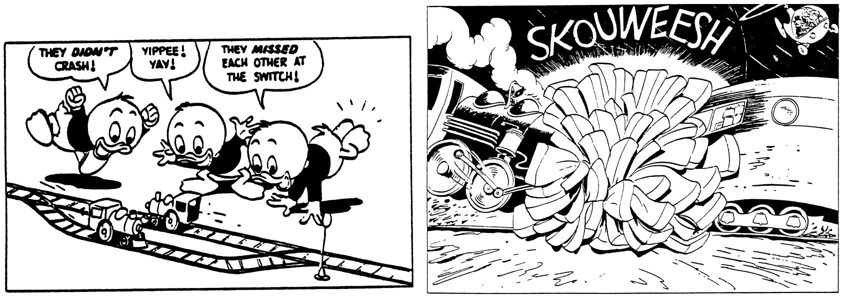

Fig. 2. Toy train as a model. The possibility to calculate the timing and location of the collision of the toy and the real trains is assumed to coincide (neutral analog). Based on a calculation with the toy trains, the location and timing of the collision of two real trains is estimated and efficient measures to mitigate the impact of the collision are prepared (constructive use of model). From Barks 1954

> *Determining the positive analogs means to validate the model, while assuming the neutral analogs to be positive ones means to constructively use the model. The constructive part of a model is in its neutral analogs.*

Models are supposed to reflect reality. But they are not identical to reality: Models are *smaller, simpler* and *closed* in contrast to reality which is always *open* (for a more detailed account, refer to [29]):

- 'Smaller' means that only a limited number of the infinite number of real processes can be accounted for. In case of an atmospheric model or an oceanic model, the unavoidable discretization means that from the overall ranges of scales only a limited interval can be accounted for. A global atmospheric model describes planetary waves and cyclones, but no boundary layer turbulence in any detail.
- 'Simpler' means that the description of the considered processes is simplified. For instance, surface friction of air blowing across the surface of the ocean is maintained by small scaled turbulent eddies, none of which can be resolved by the numerical model. Instead the overall effect is summarily described by 'parameterizations'.
- 'Closed' means that models are integrated with a limited number of completely specified external forcing functions. In case of the climate model discussed below, forcing factors like solar insolation and volcanic aerosols are crudely prescribed as estimated annual means. However, other factors like regional deforestation or desertification are not accounted for. As elaborated by Oreskes et al. [23] is this an important philosophical limitation of environmental models, as it implies that the answer of a model may be 'right' because the model is 'correct' or because the model's 'error' is balanced by an unaccounted external influence.

Because of these properties of models, they suffer from a number of limitations:

- A model is describing only part of reality. For instance, in case of an 2-d energy balance model, the effects of stationary atmospheric waves (related to topography and land-sea contract) as well as the effect of unstable polar fronts is not resolved. Thus, the meridional transport of energy in such models is often maintained by a formulation reminiscent on diffusion.
- The models can not be *verified*. We can not with certainty conclude that the model is producing 'right' numbers because of the 'right' dynamics. What we can do, is to *validate* the models by finding the simulated numbers being consistent with the observations; we may add to the credibility to the model by analyzing the dynamical system and assuring that all first, or even all second order processes are adequately accounted for.

  However, even the most comprehensive validation is not providing certainty about the skill of the models, when applied in the constructive mode, i.e., when statements are made beyond the empirical evidence the model has been validated against.

2.2 Specific Aspects of Climate Modelling

When dealing scientifically with climate, there are a number of specifics which make the field different from, for instance, classical physics (cf. [22]). One is the impossibility to conduct laboratory experiments[1] on the functioning of the *system as a whole*. Also, real world *repetitions* are unavailable, which otherwise may help to rigorously sort out if certain phenomena have emerged merely by chance or as a result of certain processes. Another specific is that a myriad of processes interact in the climate system. One could argue that the same situation would prevail in a gas, with enormous numbers of molecules interacting with each other and responding to radiations. However, the temporal and spatial scales of the climate processes vary widely, from e.g., the Hadley Cell in the tropical atmosphere to turbulent eddies in the wake of a plane. Moreover, the dynamics at different scales are different in character, and cannot be described by some similarity laws. Many of theses processes exhibit chaotic behaviour, with the overall effect that random-like variability, 'noise', emerges on all spatial and temporal scales (cf. [32]). In principle, the system is deterministic, but the many chaotic processes create a pattern of variability, which cannot be distinguished from the mathematical construct of random variations.

Because of these specific features, two fundamentally different types of mathematical models are used in climate research.

- One sort is 'quasi-realistic' and is supposed to be a substitute reality, within which the otherwise impossible experiments can be conducted. A representative of this type are 'General Circulation Models' of the atmosphere and the ocean. An alternative are models of 'intermediate complexity'.
- The other type of model, named here 'cognitive', is highly simplified and idealized. *Because of its reduced complexity* such a model constitutes 'knowledge'. Examples are 0-dimensional energy balance models [5], but also Lorenz' butterfly [18] or Hasselmann's stochastic climate model [11].

In the following we limit our discourse to quasi-realistic (GCM-type) models.

3 Quasi-realistic Climate Models ('Surrogate Reality')

The main purpose of a quasi-realistic model is to provide scientists with an experimental tool. As such, it is as complex as possible. Ideally, a quasi-realistic model generates numbers as detailed and complex as the real world (within the limits of spatial and temporal resolution). Modern climate models are

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[1] Here, following Encyclopedia Britannica, we understand an experiment as a "an operation carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis".

such quasi-realistic models. They feature detailed dynamical models (*General Circulation Models*, GCMs) of the atmospheric, oceanic and (part of) the cryospheric dynamics. But, even if they are highly complex, their skillful reproduction of real dynamics is limited to sufficiently large-scales (e.g., [27]) and to phenomena consistent with the present climate.

The limitation with respect to scales is important for paleoclimatic studies as the formation of proxy evidence is taking place on regional if not local scales. Thus, the comparison of local estimates from geological archives with GCM output, on the grid point level, is often difficult (cf. [28]).

A widely used alternative to GCMs are *Earth System Models of Intermediate Complexity* (EMICs) which often describe more climatic subsystems than the quasi realistic GCM-type models. However, the subsystems are described in less detail, so that that the overall simulations are much more efficient (in terms of computer time) but less detailed. For an overview, see [3].

3.1 GCM-type Climate Models

Quasi-realistic models are mathematical models, based on differential equations describing the fluid dynamics of air, seawater and ice. The differential equations used to describe the oceanic and atmospheric dynamics are usually the *primitive equations*[2]

For the ocean, they have the state variables 'current', with the horizontal components $\mathbf{v}_h = (u, v)$ and the vertical component w, the density ρ, the salinity S, temperature T, and pressure p.[3]

$$\rho_o \left(\frac{Du}{Dt} - \frac{uv}{a} \tan\varphi \; - fv \right) = -\frac{1}{a\cos\varphi} \frac{\partial p'}{\partial \theta} + \mathcal{F}_u$$

$$\rho_o \left(\frac{Dv}{Dt} + \frac{u^2}{a} \tan\varphi \; + fu \right) = -\frac{1}{a} \frac{\partial p'}{\partial \varphi} + \mathcal{F}_v$$

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[2] These equations are named 'primitive' not because they are simple, but because they are considered the most genuine equations describing atmospheric and oceanic dynamics. In pre-computer times, these equations could not be dealt with, and more heavily filtered equations, like the quasi-geostrophic equations were analyzed.

[3] Of the seven state variables, only four are *prognostic* variables - namely the horizontal current, salinity and temperature - whereas the vertical component of the movement, the density and the pressure are *diagnostic* variables. The present state of a 'prognostic' variables depends on the past state of the system's state variables, whereas 'diagnostic' variables may be calculated from simultaneous state variables. The vertical component w is given by the divergence of the horizontal flow (1), because for the balance of mass, i.e.. the continuity equation (1), density differences are considered irrelevant. The four thermodynamics variables p, T, S and ρ may be expressed as functions of the other two - here the density and the pressure are expressed as functions of S and T.

$$\begin{aligned}
0 &= -\frac{\partial p'}{\partial z} - g\rho' \\
0 &= \frac{\partial w}{\partial z} + \nabla_h \cdot \mathbf{v}_h \\
\rho_o \frac{DS}{Dt} &= \mathcal{G}_S \\
\rho_o \frac{DT}{Dt} &= \mathcal{G}_T \\
\rho' &= \rho'(S, T, p_o(z))
\end{aligned} \tag{1}$$

with f being the Coriolis term, a the radius of Earth, φ and θ representing latitudinal (north-south) and longitudinal (east-west) coordinates. The operators $\frac{D\cdot}{Dt}$, $\frac{\partial\cdot}{\partial\cdot}$ and ∇_h represent the , the and the horizontal divergence operator. $\mathcal{F}_u$, $\mathcal{F}_v$, $\mathcal{G}_S$ and $\mathcal{G}_T$ represent non-resolved source and sink terms, such as surface stress or radiation. The density ρ is expressed as a sum of a reference density ρ_o and a dynamically relevant deviation ρ' from that reference. Also the pressure is written as a reference p_o plus a deviation p'.

The primitive equations for the atmosphere are similar[4]. However, the state variable salinity is replaced by specific humidity q:

$$\begin{aligned}
\rho_o \left(\frac{Du}{Dt} - \frac{uv}{a} \tan\varphi \ - fv \right) &= -\frac{1}{a\cos\varphi}\frac{\partial p}{\partial \theta} + \mathcal{F}_u \\
\rho_o \left(\frac{Dv}{Dt} + \frac{u^2}{a} \tan\varphi \ + fu \right) &= -\frac{1}{a}\frac{\partial p}{\partial \varphi} + \mathcal{F}_v \\
0 &= -\frac{\partial p}{\partial p} - g\rho \\
\frac{D\rho}{Dt} + \rho(\nabla \cdot \mathbf{v}) &= 0 \\
\rho \frac{Dq}{Dt} &= \mathcal{G}_q \\
c_p \frac{DT}{Dt} &= \mathcal{Q} + \alpha \frac{Dp}{Dt} \\
p &= R_m(q)\rho T
\end{aligned} \tag{2}$$

The differential equations given above are discretized, i.e., the differential operators are replaced by difference operators[5]. This is done on a more or less

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[4] The prognostic variables are the horizontal components of the wind, temperature and specific humidity, whereas vertical movement, pressure and density are diagnostic variables. Again, any two thermodynamic variables are considered prognostic and the other two diagnostic. Differently from the situation in the ocean, the vertical movement is no longer considered to be given only by the horizontal divergence but also through the change of density (see continuity equation 2).

[5] An alternative to the use of difference operators is the Galerkin (spectral) method. In that case the equations are projected onto a finite-dimensional function space.

regular grid. As a result, the model operates no longer with continuous variables but with averages formed for the grid boxes. Finally, the "non-resolved source and sink terms" are replaced by approximate formulations, which depend only on the grid box averaged variables (*parametrizations*)

3.2 Purposes of Quasi-realistic Climate Models

Quasi-realistic models in paleoclimatic studies are used for several purposes listed below. Obviously, the separation between the first three categories is blurred.

- *Dynamical tests of hypothesis.* When hypothesis are derived from geological evidence, their dynamical consistency may be tested by a 'numerical experiment' with a climate model. An example is the effect an open Isthmus of Panama may have on the global oceanic circulation (Maier-Reimer et al., 1999).
- *Equilibrium runs* are simulations of many years, with annually repeating forcing in terms of solar radiation and possibly other factors like vegetation cover. Other aspects like concentrations of greenhouse gases and volcanic aerosols and orbital parameters, topography of ice sheets are kept constant. Such runs simulate the equilibrium climate given certain constant external conditions, mostly contemporary conditions but also various paleoclimatic episodes ('time slices'). They are done by running the model over a long[6] time. They generate time series of complete and dynamically consistent data, representing the climate statistics conditioned upon the prescribed external forcing configuration.
- In *transient runs* natural factors like solar radiations and anthropogenic factors like greenhouse gas concentrations are specified as time dependent, whereas 'slow' factors like orbital parameters are kept constant.[7] Such simulations address 'transient' climate states, in which a time dependent forcing is preventing the climate to attain an equilibrium state. Scenarios of modern Global Warming have to be dealt in this way, but also paleoclimatic variations on time scales of years and decades need to be addressed in this manner.

For the understanding of the character and problems of such models, this detail is not relevant, however.

[6] The term 'long' depends on the availability of contemporary 'supercomputer' powers, which is obviously changing in time. A simulation of 13 consecutive Januaries (e.g., [31]) was in the early 1980s a time-consuming task, as well as a hundred year simulation in the early 1990s (e.g., [6]) or a thousand years run in the mid 1990s (e.g., [34]). At any given time, a long run is usually a simulation with a state-of-the-art model describing the atmospheric dynamics in detail and the oceanic dynamics without resolving the baroclinic eddy dynamics. The wall clock time of such simulations is sometimes of the order of several months.

[7] This statement is limited to climate models which describe atmosphere and ocean in detail, whereas ice sheets are mostly kept constant.

- A very recent application concerns the analysis of environmental states. Because of many degrees of freedom and practical barriers rendering certain variables unobservable, a complete analysis of the state's system is but impossible. However, an intelligent use of dynamical knowledge encoded in quasi-realistic models allows for the dynamically consistent interpretation of sparse, and to some extent uncertain, observations [24]. Such tools are called *data assimilation*, and their output 'analysis'. Note that analyzes are merely best guesses of the real situation; it is a skillful approximation of the real situation; sometimes measures of certainty of the approximations are given.

  In this way, consistent and complete data bases of the system are provided.

Quasi-realistic models do not provide immediately knowledge. Being high-dimensional and complex, the numbers need a skillful analytical treatment before conclusions can be drawn. The knowledge is hidden in the numbers; to extract this knowledge, the output must be interpreted with the help of cognitive models, i.e., concepts derived from dynamical reasoning, or from statistical analysis of observational evidence and numerical simulations, or combinations thereof [33].

4 Equilibrium, Transient and Data-driven Model Simulations for Reconstruction of Historical and Paleoclimate

4.1 Equilibrium Runs

The purpose of equilibrium runs is to simulate an equilibrium climate, given the repeated annual cycles of radiation and the constant values of greenhouse gas concentrations. Most equilibrium runs address present day climate – such simulations are named 'control' runs – but many others have been made to simulate specific paleoclimatic periods, like the mid Holocene (e.g., [15]), the Last Glacial Maximum [16] and the Eemian [21]. These simulations produce climate statistics of, for instance, 'the' Eemian, as opposed to atmospheric and oceanic state at specific times, e.g., 119. 210 year bp.

An important point, often overlooked by geoscientists, is that climate is varying without the presence of any time dependent forcing (except for the prescribed but constant annual insulation cycle). As an example, Fig. 3 shows the annual mean temperature in a control run extending over 1000 years, averaged over the whole globe and over Europe. The time series are characterized by irregular variations with significant deviations from the 'normal' (the long term mean). For instance, in the 6th century, prolonged warming appears in Europe, with maximum anomalies of more than 0.5K. That is, in climate there is something like "smoke without fire". In fact, a proper cognitive model of climate is that of a random process, which characteristics are conditioned by certain external factors[8]. When the latter are fixed, the characteristics are fixed. When they are time dependent, the characteristics are time dependent as well.

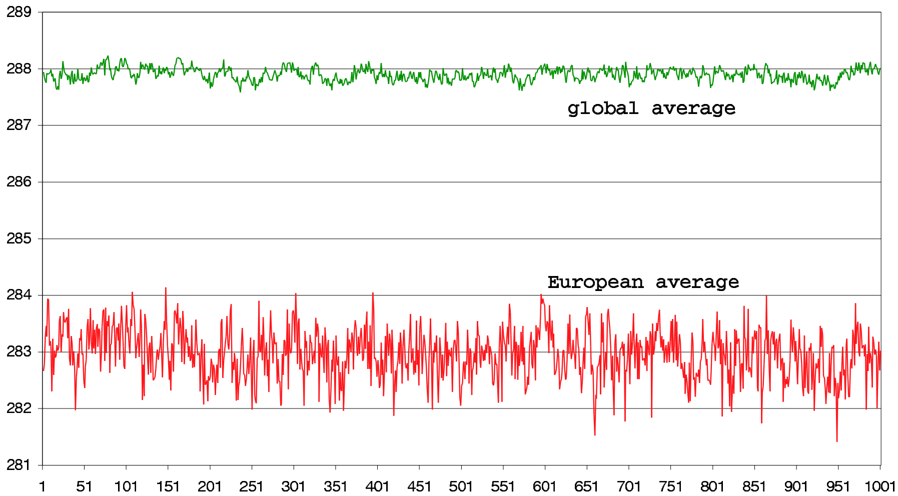

Fig. 3. Air temperature near the ground level in a thousand years integration, averaged over the whole globe and over Europe.

The output of control runs allows to determine almost all statistical characteristics of climate[9] as transports of energy and momentum or various measures of variability (e.g., spectra, modes of variability or teleconnections). Control runs have been shown to reliably reproduce the large-scale aspects of contemporary climate (e.g., [25]). Control runs prepared with different climate models produce rather similar results on large scales, whereas on regional scales there may be marked differences [8].

The "internally generated" variability, as simulated in control runs, has significance for the analysis of atmospheric and climate dynamics, as the system is masked by noise [32]. The noise is constitutive as it generates variability, but it hampers at the same time the detection of natural and anthropogenic signals [12], in particular for assessing the reality of Global Warming (e.g., [13]).

4.2 Transient Runs

When time varying external forcing, e.g. related to changing greenhouse gas concentrations, volcanic aerosol loading, changing land use and vegetation,

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[8] In that sense, quasi-realistic climate models are a kind of conditional random number generators, albeit a very complex one.

[9] A more precise wording would be: Climate is the statistics of weather. These statistics are described by parameters, like moments

are exerted on a GCM, the simulated climate is no longer in equilibrium but changes in the course of time. The most prominent type of such simulations are the climate change scenarios (e.g., [7]) as summarized in the IPCC reports. Other applications refer to the effect of changing greenhouse gas and industrial aerosol loadings since preindustrial times [26] or the effect of changing solar output [9] and volcanic aerosol loadings.

In the following a brief overview of a recent simulation of the time 1550-1800 with the climate model ECHO-G [17], exposed to varying solar output and volcanic aerosol loadings is given (Fig. 4)[10].

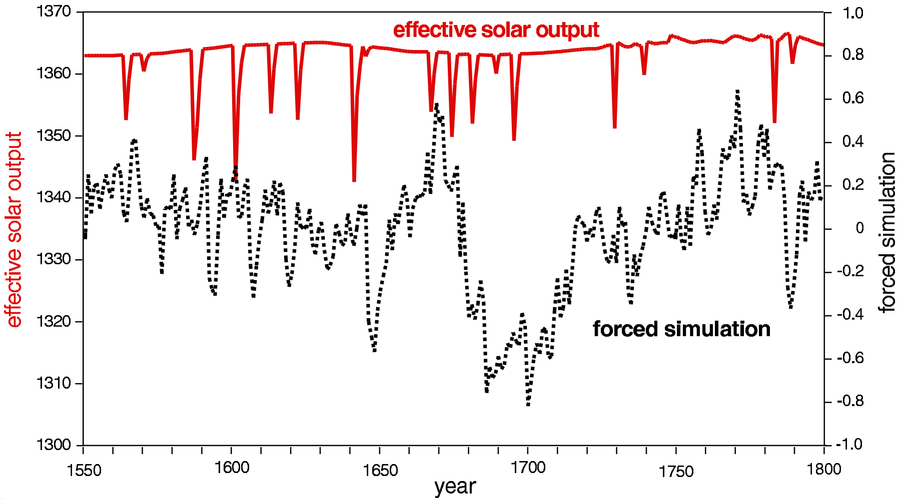

Fig. 4. Forcing time series of effective solar output used in the transient simulation of the *Late Maunder Minimum* (solid) and the simulated Northern Hemisphere temperature (dotted).

The purpose was to simulate a marked wide-spread cooling which appeared in 1675-1710 in Europe (Fig. 5). Maximum values of more than -1.2K in Eastern Europe, -0.5K in many parts of Germany, France, Italy and Greece were reconstructed from historical reports and proxa data [19]. Everywhere else, weak cooling of less than 0.5K was reconstructed. Weak warming was estimated to have taken place only a few spots in Northern Norway, Iceland

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[10] The CO_2 and methane atmospheric concentrations were derived from air trapped in Antarctic ice cores [2], [10]. The variations of solar output and the influence of volcanic aerosols on the radiative forcing were taken from Crowley [4], who used the number of sun spots after 1600 AD and concentrations of cosmogonic isotopes in the atmosphere before 1600 AD. The forcing due to volcanic aerosols was estimated from concentrations of sulphuric compounds in different ice cores, located mainly over Greenland. These forcing factors were then translated to effective variations of the solar constant in the climate model.

and south-eastern Greenland. The period is named *Late Maunder Minimum* (LMM) and coincides with the second half of a period of particularly low numbers of sunspots and a reduced solar activity. During this period several large volcanic eruptions took place. For further details, refer to Chapter XX in this volume.

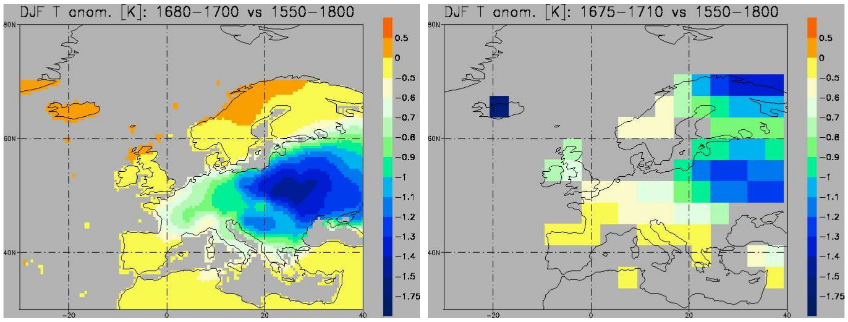

Fig. 5. Reconstructed DJF temperature conditions during the LMM [19] (left) and simulated in a transient simulation using historical solar output and atmospheric volcanic aerosol loading

During the winters 1675-1710 a marked global cooling (relative to the 1550-1800 time average) was simulated (Fig. 5). When the 1675-1710 episode is simulated again with a somewhat different initial state, a similar anomaly is formed. Thus, the emergence of the anomaly is related to the anomalous radiative forcing. The reconstruction compares well with the modelling result with cooling almost everywhere, with maximum values of -1.2K and more in Eastern Europe, and -0.5K and more over most of Europe. No warming spots are simulated, and Northwest Russia/Northern Norway is simulated as being very cold, a fact not supported by the sparse historical evidence available to us. However, the skill of the reconstruction in the later areas is considered as rather low. We conclude that the intensity and timing of the European cooling represents a positive analog of the model (Fig. 1).

Little is known about the temperature conditions during the *Late Maunder Minimum* outside Europe. Therefore, we cannot really validate the model results on a global scale; instead we may consider the model output as a physically based, plausible hypothesis of what was going during that time outside of Europe (neutral analog; Fig. 2). Because of the presence of climatic noise on all time scales, we cannot expect that all details, in terms of spatial patterns and temporal evolutions, are reproduced. We would, however, expect that the broad spatial patterns as well as the time mean structure, be reproduced.

The global temperature anomaly is displayed in Fig. 6. It is dominated by a strong cooling, of -1K and more, in Northeast Canada, Greenland, the Northern North Atlantic, while on the Northern Hemisphere continents a weaker cooling, of -0.5K and more, takes place. On most of the rest of the

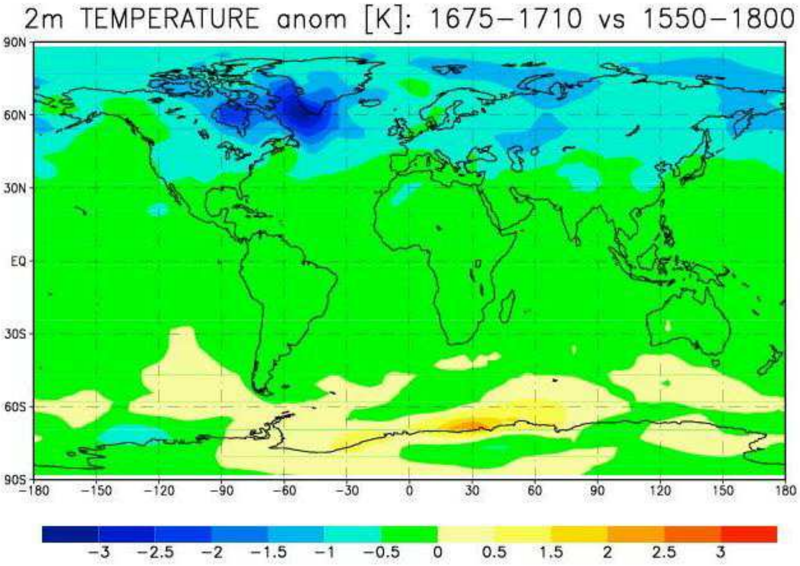

Fig. 6. Simulated annual mean global cooling during the LMM, relative to 1550-1800 time mean.

globe a cooling of up to -0.5K is simulated, with isolated warming spots on the Southern Hemisphere. Thus, the event is a worldwide phenomenon, which is associated with largest anomalies in the North Atlantic. In the Labrador Sea, ice conditions are much more severe than before and after the LMM event, with the ice coverage increased by up to 25% (not shown). The overall cooling is consistent with evidence from world-wide coral proxy data.

We conclude that the simulated reduction of temperature during the model years 1675-1715 is not accidental, but is reproducibly related to the anomalous combined volcanic and solar forcing.

4.3 Data Driven Simulations

In the type of simulations discussed so far, data serve mainly as boundary conditions, like time variable CO_2 concentrations, and as a reference to compare the simulation results with. The situation is different in case of *data driven simulations*. In that case the data are considered the primary information but incomplete in their spatial and temporal coverage. Also they are to some extent uncertain. Then, the model is used to ‘interpolate’ the observational evidence. Thus, the models are, in a sense, subordinated to the data.

The concept is based on the state space formulation, with state variables Φ, a dynamical model $\mathcal{F}$, forcing η, observed quantities ω, and a function describing the observation process $\mathcal{G}$:

$$\Phi(t) = \mathcal{F}(\Phi(t-1), \eta(t-1)) + \delta \qquad\qquad \omega(t) = \mathcal{G}(\Phi(t) + \epsilon \tag{3}$$

with errors terms ϵ and δ representing the incompleteness of the dynamical model $\mathcal{F}$, and the errors in the observation process $\mathcal{G}$. The former is the *state space equation* and the later the *observation equation*. The system is integrated forward in a step-like manner. First, given a valid state $\phi(t-1)$, a preliminary new state $\phi^*(t)$ is calculated with $\Phi^*(t) = \mathcal{F}(\Phi(t\text{-}1),\eta(t\text{-}1))$. Then an expected observation $\omega^*(t) = \mathcal{G}(\Phi^*(t)$ is derived. Usually, $\omega^*(t)$ deviates from the true $\omega(t)$. Therefore, a new *best guess* is determined through

$$\Phi(t) = \Phi^* + \mathcal{K}(\omega^*(t) - \omega(t)) \tag{4}$$

with a suitable operator $\mathcal{K}$.

For paleoclimatic reconstructions, the state space variables are large scale variables, like the principal components of wind at some level or sea surface temperature. The dynamical model can be a quasi-realistic model, as described in Sect. 4, the observable tree ring densities or other proxy data, and the $\mathcal{G}$ an *upscaling operator* (e.g., [1])

The system, named *Data Assimilation Through Upscaling and Nuding* (DATUN) is presently under development [30].

5 Conclusions

In this discourse we have discussed the scientific approach of ‘modelling’, which is usually not conceptualized. Almost all scientific disciplines, classical natural sciences, environmental sciences, social and cultural sciences, use the term ‘model’. A joint property of all these models is that they refer to a complex part of reality and that they are simpler than reality. Otherwise models vary widely in concept, design and purpose. Nevertheless everybody seems to believe that his or her use of the term ‘model’ is the genuine one supposedly understood by everybody else. Examples are mental maps in social sciences, digital elevation maps in earth science and world models in economy. Same models are static, like a map, others are dynamical, including a predictive capability. Some models are scientific constructs, others are social or historical constructs.

In interdisciplinary cooperation, then, severe misunderstandings emerge and hinder the flow of ideas and knowledge between the different traditional branches of science. This is in particular a problem in modern paleoclimatology, which is rapidly expanding across traditional disciplinary borders.

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