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Editorial

Understanding the Earth as a Complex System – recent advances in data analysis and modelling in Earth sciences

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Abstract. This topical issue collects contributions exemplifying the recent scientific progress in the development and application of data analysis methods and conceptual modelling for understanding the dynamics of the Earth as a complex dynamical system. The individual papers focus on different questions of present-day interest in Earth sciences and sustainability, which are often of paramount importance for mankind (recent and future climate change, occurrence of natural hazards, etc.). This editorial shall motivate the link between the different contributions from both topical and methodological perspectives. The holistic view on the Earth as a complex system is important for identifying mutual links between the individual subsystems and hence for improving the physical understanding of how these components interact with each other on various temporal as well as spatial scales and how the corresponding interactions determine the dynamics of the full system.

1 Introduction

During the last decades, the increasing public and scientific interest in geoscientific problems has triggered enormous efforts to obtain, analyse and interpret data containing substantial information about the dynamics of the complex system "Earth". With the availability of new sources of data in terms of extensive computer models, continuous ground- or satellite-based monitoring and extensive measurement campaigns, novel techniques not only for recording and storing these data, but also for their statistical evaluation and data-based modelling had to be developed. Altogether, these developments have led to an enormous progress in our understanding of the mechanisms responsible for the dynamics of the different components of the Earth system, such as atmosphere, biosphere, lithosphere, etc.

Various novel concepts, among them many originated in the theory of nonlinear dynamical systems, have recently been introduced and subsequently applied to various practical questions from different fields of Earth sciences [1]. With this gradually extending range of applications, the interest of practitioners from these fields in using existing and in developing new

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sophisticated methods for data analysis and modelling for better understanding the observed phenomena has been continuously increasing. Whereas the first developments have mainly been triggered by the activity of statisticians or physicists interested in interdisciplinary problems, these practitioners have gradually started to explicitly formulate their specific requirements, which has lead to many extremely fruitful collaborations between Earth scientists on the one hand, and mathematicians and physicists on the other hand.

The individual manuscripts collected in this topical issue deal with problems such as recent climate change, the occurrence and predictability of extreme events, and the dynamical behaviour of the different components of the complex system Earth in past, present, and future. This editorial is intended to give a brief motivation of the holistic interdisciplinary approach to the complex system "Earth" which is common to all papers of this issue and to put them in a general context. Sec. 2 contains a short overview about important historical developments in time series analysis and complex systems sciences, which have been triggered by specific geoscientific questions. Sec. 3 describes some known facts about interactions between different components of the Earth system, which calls for a common treatment with the help of sophisticated mathematical and statistical methods. Four particular types of questions that build the backbone of this topical issue are discussed in some detail in Sec. 4. It has to be noted, however, that the choice of these four fields reflects the subjective point of view of the editors on which specific problems are currently "at stake" in Earth sciences, and that this list could be further extended by multiple other questions.

2 Geoscientific triggers of historical developments in time series analysis and modelling

Developments in data analysis and modelling techniques have been stimulated early on by geoscience problems. The periodic-like phenomena in the Earth system have triggered a number of techniques for describing and predicting cyclic processes. Around 1867, Lord Kelvin formulated the method of harmonic analysis for the study of ocean tides [2]. In the late 1890's, Schuster opened the statistical field of power spectra by developing the periodogram for identifying periodicities in sequences of observations of earthquake events [3] and in the famous record of sunspot numbers [4]. Autoregressive modelling was introduced by Yule as an alternative to the periodogram of Schuster for the study of the sequence of sunspot numbers [5]. While Schuster assumed that random noise would not affect the "true" amplitude and phase of a cycle, Yule argued for a more realistic approach, in which the amplitude and phase of a signal could change due to random perturbations. Walker followed a similar path in his pioneering study of the Southern Oscillation, the atmospheric component of the El Niño - Southern Oscillation (ENSO) phenomenon, and in his attempts of predicting the monsoon in India [6,7]. Later, Tukey introduced modern approaches for the analysis of periodic phenomena in geosciences, including the cross-spectrum for the analysis of seismic waves, complex demodulation and bispectrum analysis [8,9].

As a common problem in different disciplines of Earth scienes, which is probably most pronounced in the field of palaeoclimatology (see Sec. 4.1), the appropriate statistical treatment of unevenly spaced time series has attracted increasing interest in the last decades. In particular, techniques for spectral analysis of unevenly spaced time series have been introduced and discussed in this and related fields, e.g. by Lomb and Scargle [10,11].

Problems originated in the Earth sciences have inspired many developments in methodological approaches other than the ones aiming at analysing periodic phenomena. The need to cope with natural hazards such as floods and droughts, encouraged the development of methods for the analysis of extreme values, such as the contributions of Gumbel to the theory of the analysis of extreme values inspired by meteorological and hydrological phenomena [12,13]. Also from hydrology sprung the concept of long range dependence or long memory. It was first described in the analysis of the water levels of the Nile river [14] as the tendency for a flood year to be followed by another flood year. The concept of long range dependence is closely related to the concept of self-similarity [15] – both are manifestations of scale invariance, or absence of a characteristic dominant scale in a phenomenon.

Wavelet analysis has been developed as a concept that allows for both the analysis of scaling properties and the detection and quantification of instationary periodicities or pseudo-cycles (two features that are common to many time series from the Earth sciences) [16,17]. Motivation for the corresponding methodological progress over the last two decades has been gained by several specific problems from different geoscientific disciplines, including the understanding of certain modes of climate variability, the multi-scale analysis of seismic signals, or the characterisation of ocean waves. Extensions to unevenly spaced time series are meanwhile also available (see, e.g., [18]).

The pioneering work of Lorenz in the 1960's on weather forecasting demonstrated the limitation of linear models to the description of the Earth's climate and was an essential contribution to the modern theory of chaos [19–21]. Lorenz popularised the concept of the sensitivity of a dynamical system to initial conditions by the term "butterfly effect", referring to the effect of a butterfly flapping its wings on weather forecast.

Digital computers played a fundamental role in the development of chaos theory and nonlinear dynamics. The advent of cheap and easily accessible computational tools revolutionised the way data could be stored, analysed and modelled. Modern geosciences typically deal with an unprecedented amount of data from a variety of sources, including continuous monitoring through digital sensors, satellites orbiting the Earth that yield huge amounts of information at regular spatial and temporal scales, and outputs from model runs. The mutually stimulating development of geosciences and of methodological approaches for analysing and modelling the vast amount of geoscientific data now available has therefore never been so crucial. Building on the successful historical tradition in which new methods for data analysis and modelling were triggered by geosciences problems, the cross-fertilisation between data from Earth sciences and methodological techniques (often originated in the field of physics) takes place at an increasing pace, and is fundamental for the study of the Earth system.

3 Viewing the Earth as a complex system

The Earth is a highly complex system formed by a large variety of sub-systems (biosphere, atmosphere, lithosphere, as well as social and economic systems etc.), which interact by the exchange of matter, energy and information. As the result of these interrelations, the Earth can be interpreted as a complex and evolving network. One may consider each subsystem separately, but the growing understanding of the whole system Earth suggests that one should take into account the interactions between these subsystems. Of course, within the framework of the debates on anthropogenic climate change, the issue of understanding the dynamics of the climate system as one major component of the system Earth has received paramount interest. Its importance is also triggered by the possible impacts of climate change on human society and, more generally, on the entire biosphere. As a consequence, a couple of papers in this issue discuss climate-related problems. However, the climate system is not fully isolated, but has different links to other subsystems.

To give a particularly important example for interactions of the climate with other subsystems, one may list multiple links between the dynamics of the Earth's body and the climate system:

1. On very long time scales, tectonic activity and the resulting motion of continental plates is an important trigger for the formation of oceanic currents, which transport vast amounts of energy in terms of heat that is successively transferred to the atmosphere and thus determines the climate on large (both temporal and spatial) scales [22]. Examples for corresponding changes of the global climate in the past include the opening of a deep-water connection in the Drake passage between South America and the Antarctic, which allowed the formation of the Antarctic circumpolar current (ACC) that triggered the first large-scale glaciations of the South pole region [23], and the closure of the seaway between North and South America, which marked the end of the Pliocene and started an era of increasing glaciation in both polar areas [24].

2. The presence of ice sheets in high latitudes is known to influence both the dynamics of the Earth's body (via pressure forces) and the climate system (e.g. through the ice-albedo feedback, which amplifies the cooling effect by an increasing reflection of solar irradiation). Vice versa, the disappearing of polar ice sheets is clearly a result of gradual long-term climate changes, but can also trigger abrupt climate transitions, as has been frequently observed in the Earth's history of the last 1 00,000 years in terms of Heinrich [25,26] and Dansgaard-Oeschger events [27,28].
3. Whereas the above mentioned links act on time scales of centuries to millennia or even much longer (e.g. those related to palaeoclimatic problems), there is also scientific evidence for relevant interrelationships on shorter scales, for example, in terms of certain electromagnetic activity in the atmosphere before the occurrence of severe earthquakes [29].

Following these examples (the given list is far from being complete), one has to conclude that the dynamics of land masses, oceans, ice sheets etc. is closely linked to climate, which calls for a holistic treatment of these different systems. Indeed, present-day climate models usually consider some of the mentioned feedbacks, in particular those related to oceanic dynamics, ice sheets, or biosphere, as long as they are believed to act on the time scales of interest.

In addition to these physical links, there are also strong methodologic links between, for example, the fields of climatology and geodynamics, which are motivated by similar kinds of problems or challenges for data analysis and modelling in different disciplines. In particular, the emergence of natural hazards and other extreme events refers to climate variations as well as seimologically triggered events, and has thus stimulated methodological developments in the same directions in both disciplines, including the observation of the existence of characteristic scaling laws, which is commonly treated within the framework of self-organised criticality, or the description of the corresponding dynamics by means of complex networks.

In general, contemporary Earth sciences deal with numerous problems of interdisciplinary interest. These problems include, but are obviously not limited to the understanding of transition phenomena, the understanding and forecasting of the "regular" dynamics of the subsystems as well as certain types of events (such as extremes or abrupt regime shifts), and the conceptualisation of a high-dimensional complex dynamics by simplified low-dimensional models. Note that the mentioned kinds of questions are not specific to Earth sciences, but do also commonly occur in other physical systems and may thus to a large extent be tackled by concepts originated in the physical sciences. Hence, using methods developed for studying problems from one specific geoscientific discipline may provide key insights for coping with phenomena in other (not necessarily Earth science) disciplines as well.

4 Recent developments in data analysis and modelling in Earth sciences

4.1 Deciphering palaeoclimate variability

The development of strategies for mitigation of or adaptation to present-day climate change requires the understanding of the Earth's climate system with its various major components, such as the El Niño/ Southern Oscillation, the North Atlantic Oscillation or the Monsoonal circulation system. Besides the investigation of the recent climate dynamics (Sec. 4.2), the study of past climate variability provides insights in potential heavy or rapid changes and different regimes (e.g. glaciations [30]), as well as their impacts (e.g. enhanced landslide generation [31]). However, palaeoclimate variability is available only by measuring and interpreting proxy data, influenced by many other factors than by climate. This attenuates the reliability or even hides the climate dynamics. Further problems often occur in the form of unevenly spaced time-scales and because one is not able to repeat measurements in the field.

In this topical issue, several approaches are discussed which may help to cope with such problems:

Braun [32] has studied several measures of regularity (Rayleigh R, minimum and maximum standard deviation of events) in order to distinguish between different forcing scenarios, e.g. ghost stochastic resonance, in threshold-crossing events, in particular Dansgaard-Oeschger

	Deciphering palaeoclimate variability	Trends, cycles and extremes in present-day climate	Spatio-temporal interrelationships	Dynamical processes in atmosphere and ocean
Deterministic modelling			Handorf and Dethloff	Handorf and Dethloff, Orgis *et al.*
Linear time series analysis	Mudelsee	Barbosa , Collet *et al.*, Hamed, Mudelsee	Hamed, Collet *et al.*	
Extreme value statistics		Huong Hoang *et al.*, Laubrich and Kantz, Rust, Rust *et al.*	Rust *et al.*	
Multi-scale analysis		Mabille and Nicolay, Pisoft *et al.*	Mabille and Nicolay, Pisoft *et al.*	Balasis and Eftaxias, Hawkins and Warn-Varnas
Complex networks			Donges *et al.*, Jimenez *et al.*	
Stochastic modelling	Braun, Crucifix and Rougier	Laubrich and Kantz		Paradisi *et al.*

Fig. 1. Overview of the topical and methodological contents of this topical issue.

events. He has found that the often used measures Rayleigh R and minimum standard deviation of events are rather inefficient to distinguish between ghost stochastic resonance and a simple random occurrence of events (at least in case of only 12 events available).

A solid analysis of changes of trends in time series is in particular important in the discussion of global climate change. Mudelsee [33] gives a thorough explanation for a procedure to detect break points in climate time series. The introduced approach involves the consideration of dating uncertainties, uneven time scales, non-Gaussian distributed data, and serial dependence. Moreover, it provides confidence intervals for the found break points.

In order to discuss the question "When the next glacial onset can be expected?", Crucifix and Rougier [34] have used a phenomenological climate model (Saltzman model) which is tuned by palaeoclimate observations. They combined low-order non-linear dynamical systems with the palaeoclimate records using Bayesian statistics and performed the prediction by the particle filter. Their tentative results indicate a glaciation onset not before 50,000 years from now.

4.2 Trends, cycles and extremes in present-day climate

The present-day climate is the focus of intense scientific research aiming to identify, characterise and attribute causes to present-day climate change [35]. These issues spread beyond the scientific research realm and became pressing questions also for policy makers and the society in general.

From a climate change perspective, the identification of trends in the climate system is of paramount importance. The task is hindered by the comparatively short length of the instrumental records and their limited geographical coverage before the advent of satellites in the mid-70's. This is not only a limitation for the robust identification and quantification of trends, but also hampers the distinction between trends in climate parameters and inter-annual variability associated with natural modes of variability corresponding to phenomena such as the El Niño/Southern Oscillation or the North Atlantic Oscillation.

The periodic and pseudo-periodic variations in the present-day climate are not only important to better quantify long-term variability, but also are of interest in themselves. The seasonal cycle reflecting the annual variability in solar radiation is often the strongest signal in climate records. The quantification of seasonal variability and its response to a changing climate is therefore of particular relevance, particularly considering that many organisms and ecosystems are adapted to seasonal events in their environment. The study of pseudo-periodic phenomena is particularly relevant for understanding mechanisms and causes of climate variability, while offering some possibilities for climate forecasting at intermediate time scales.

The role of extremes in a changing climate is a fundamental aspect when it comes to strategies for adaptation to and mitigation of climate change impacts. The analysis of extreme events in climate parameters assumes particular relevance since changes in the timing and magnitude of rare events are potentially problematic in terms of socio-economic consequences, and difficult to analyse and predict from past observations.

In this topical issue new approaches are discussed for the analysis of trends, cycles and extremes in present-day climate: Mudelsee [33] suggests a solid approach for the detection of trend changes as a special case of dynamic transitions in climate time-series. He illustrated the technique by applying it to Arctic river runoff data, indicating a sudden change towards a positive trend of river runoff in 1973. Hoang et al. [36] discuss the concept of trend and introduce the notion of multidimensional trends in the study of European air temperature time series. They discuss the nonparametric estimation of trends and the relation between trends in mean and in variance. They also address trends in extreme values and introduce a new approach to test if trends in extremes result from the trends in the mean and variance. Laubrich and Kantz [37] also find a clear association between mean and variance, in this case in atmospheric boundary layer wind speed. They describe in detail the wind speed statistics and provide a stochastic model for wind speed simulation based on a geometric autoregressive process.

Concerning cycles in present-day climate, Mabille and Nicolay [38] discuss the detection of pseudo-periodic cycles of 2 to 4 years in air temperature records. They apply the continuous wavelet transform to identify these periods in millennial temperature reconstructions, as well as in temperature time series from a model, from reanalysis and from individual stations. They also discuss the relation between these pseudo-periodic cycles and phenomena such as the ENSO and the NAO. Pišoft et al. [39] introduce another technique also based on the continuous wavelet transform, the pseudo 2-D wavelet transform, for the analysis of atmospheric variability. They identify a pseudo-periodic cycle of about 8 years in air temperature time series from two different reanalysis datasets and investigate its spatial domain of presence in some detail. Barbosa [40] discusses the detection of changes in the seasonal cycle of air temperature records and presents a method based on autoregression for discriminating between trends in the mean and trends in the seasonal pattern.

The link between seasonal variability and the occurrence of extreme events is explored by Rust et al. [41], who introduce a new approach for modelling the seasonal variability of extreme daily precipitation in the UK. They explicitly model the annual cycle with a generalised extreme value distribution with time-dependent parameters and are able to identify spatial patterns of variability in return levels of precipitation around the UK. The modelling of extreme events is also addressed by Rust [42]. Based on a simulation study, he discusses the influence of long range dependence in the modelling of extreme values with the generalised extreme value distribution. This is particularly relevant since many geophysical time series exhibit long range dependence and, as demonstrated by Rust [42] in this topical issue, failing to take it into account can lead to inaccuracies in the resulting return levels.

4.3 Spatio-temporal interrelationships

Most processes in the system Earth are characterised by complex spatio-temporal dynamics. Despite much methodological progress made in the last decades, there remains an ongoing challenge to develop techniques for modeling the underlying complex systems and for analysing observational as well as simulated data.

Most simulations in climatology are based on circulation models. Handorf and Dethloff [43] analyse an advanced atmospheric-ocean general circulation model and use the corresponding simulations to study teleconnections, i.e. long-range spatial connections, in the Northern Hemisphere. They apply two statistical approaches: correlation analysis and empirical orthogonal functions. The latter one is often called principal component analysis (PCA). This way they identify two different climatic regimes and they also forecast future changes in their strength. Collet et al. [44] combines two kinds of linear statistical models to describe hydraulic inflows in various time scales: PCA and generalised ARMA (auto-regressive moving average). This combination indeed enables an appropriate simulation over days till years.

Another important question in this context is whether or not observed time series from different subsystems are interrelated. This is especially difficult to test in geophysical time series because they have typically some memory in time, i.e. they are correlated in time, or in geophysical terms: they are persistent. Hamed [45] applies a generalised test for such correlated time series to compare the Nile flow time series with a reconstructed Northern Hemisphere temperature record. By regarding the correlation in the test, no significant interrelation can be inferred. This is in contrast to results from the application of traditional test statistics, i.e. the latter one leads to artifacts in such cases.

Networks with complex topology are a new approach to model spatio-temporal dynamics. Such complex networks are systems composed of a very large number (thousands and even millions) of nodes and are characterised by a complex topology and by complex types of interactions. The dynamics of nodes can be regular or chaotic; the topology can be random or somehow ordered, can include short- or long-range interaction; the types of interaction can be linear or non-linear, constant or changing in time, etc. The emergence of synchronous behaviour in such networks is one of the new and challenging problems in the study of dynamical systems [46,47]. The application of complex network theory to climate science is a very young field, where only few studies have been reported recently [48–50]. It has already been shown that this approach enables novel insights into the topology and dynamics of the climate system over many spatial scales ranging from local to global properties, and one can associate them with teleconnection patterns in the atmosphere, e.g. the North Atlantic Oscillation (NAO). On the global scale, climate networks were found to possess 'small-world' properties due to long-range connections (edges linking geographically very distant vertices), that stabilise the climate system and enhance the information transfer within it. Donges et al. [51] develop a rather general method to extract and characterise such a complex network from climate data sets. It is important to emphasise that nonlinear characteristics, such as mutual information are essential here Jiménez et al. [52] analyse seismic data from the network perspective. Based on a subtle clustering analysis, they give arguments that the occurrence of a specific earthquake in Spain might have been due to a reservoir impoundment.

4.4 Dynamical processes in atmosphere and ocean

The characterisation of complex processes by rather simple scaling laws is highly attractive and has a lot of history in Earth sciences. The most famous one is the Gutenberg-Richter law in seismology [53], but others are strongly discussed in atmospheric turbulence. However, when looking in more details, one often finds that one has to differentiate and ends up in various scaling laws, sometimes even in an infinite spectrum of scaling exponents. Therefore, other concepts are very important to include too. A main problem is that these approaches have to be applicable to non-stationary data.

Balasis and Eftaxias [54] apply the concept of non-extensive entropy recently developed in statistical physics to analyse geomagnetic activity. This way they can clearly distinguish between the structure of intense magnetic storms and pre-storm activity. Additionally, they find some scaling law for magnetic storms. Paradisi et al. [55] use another concept based on renewal theory in stochastics to study turbulence data from the atmosphere. This enables them to distinguish abrupt transitions of intermittent structures observed there. Laubrich and Kantz [37] develop a stochastic modelling approach which mainly focuses on the increment statistics of turbulence. They demonstrate the strong potential of their approach by analysing boundary layer wind speed which is highly non-stationary.

Another important problem in the turbulent atmosphere is the understanding of transport and mixing of tracers there; especially the influence of chemistry on this turbulent mixing has been not much studied so far. Based on a globally uniform Lagrangian transport scheme, Orgis et al. [56] study ensembles consisting of several millions of tracers which is much more than others did so far. This allows them to find significant changes in the atmospheric mixing from polar regions into lower latitudes.

A multi-scale analysis based on the continuous wavelet transform is applied by Hawkins and Warn-Varnas [57] to the study of the dynamics of internal gravity waves. They make a quantitative assessment of the dispersion relations for internal waves in the strait of Luzon and conclude that they are in agreement with the Korteweg-deVries theory of wave propagation.

5 Conclusions

Certainly, the contributions contained in this issue cannot cover all aspects of data analysis and modelling in Earth sciences. Nevertheless, these contributions will give a view on the state of the art in this field and may initiate further work in these promising directions. The numerous ongoing challenges in various fields of geoscientific research will surely serve once more as a trigger for corresponding methodological developments. As editors of this volume, we hope that the papers collected here will stimulate many new projects at the "hot spots" of Earth sciences.

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