

Climate Change Dynamics and Modeling: Future Perspectives

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1. Introduction

This preface to the Special Issue titled “Climate Change Dynamics and Modeling: Future Perspectives” presents eight articles, largely focused on a range of interdisciplinary issues related to climatic changes. The main goal of the Special Issue is, first and foremost, to break through recent innovative findings in the field and to explore new approaches for improving climate models, climate predictions, and climate projections. The articles of the issue furnish a representative overview of significant study cases that also show new avenues for improving forecasts and projections. Furthermore, they introduce new knowledge to scientists working in different disciplines related to the climate as well as to interested scholars.

It is well known that the history of the climate has ancient origins. In fact, the Greek term “klima” designated the inclination of the Sun’s rays with respect to the Earth’s surface, thus testifying to the understanding of the correlation between the flow of solar energy and daily and seasonal temperature variations. It is important to understand how dynamic and wet processes, clouds, and convection control the Earth’s climate sensitivity, changes in the hydrological cycle, and natural variability. Strong precipitation and high temperature can cause increased carbon accumulation in plants and soil due to vegetation growth, or increased carbon release into the atmosphere. A description of climate involves a broad range of skills, corresponding to several domains of science including physics, chemistry, biology, and geology. Due to the complexity of climate, most of the analyses dedicated to the quantitative estimation of climate change or climate variability are based on the employment of numerical models. Furthermore, in addition to the usual modeling techniques, given the amount of data to be pre-processed and/or modeled, when necessary, machine learning techniques (including deep learning) are used; for example, for the analysis of historical series (big historical/heterogeneous data), or even for model training [1–3].

2. 2021. Nobel Prize

The 2021 Nobel Prize in Physics was awarded to three scientists who have made “groundbreaking contributions to our understanding of complex physical systems”. Half of the prize was jointly awarded to Syukuro Manabe and Klaus Hasselmann “for the physical modeling of the earth’s climate, quantifying variability and reliably predicting global warming” and the other half to Giorgio Parisi, “for the discovery of the interaction of the disorder and fluctuations in physical systems from the atomic to the planetary scale”. Although there is no univocal definition of what “complex systems” are, this term refers to a very large number of interacting components, often governed by intrinsically random dynamics, which make their interpretation very difficult with deterministic methods of classical mechanics. Simple rules of interaction that underlie the dynamics of elementary microscopic constituents can generate extremely complicated macroscopic behaviors, in a hierarchical crescendo of self-organized complexity from small to large scales. The example par excellence is given by the Earth’s climate, which results from the complex



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interaction of a myriad of subsystems, which involve different spatial scales and numerous coupled variables.

Syukuro Manabe can be considered the founding father of global climate models. More than half a century ago, he exactly described, for the first time quantitatively, the key role played by greenhouse gases in the atmosphere. The greenhouse effect plays an essential role in determining the equilibrium point of the planet's energy balance, so much so that in a simplified model in which the Earth had no atmosphere, simple thermodynamic considerations would lead to an average temperature of $-15\text{ }^{\circ}\text{C}$, preventing in fact life on Earth as we know it. At equilibrium, the energy received by the Earth must compensate for that which is reintroduced into space, and if the latter decreases due to greenhouse gases, the temperature of the planet must increase to ensure a greater flow of energy out (as described by the Stefan–Boltzmann's law for the black body $I \propto T^4$). Manabe studied the influence of carbon dioxide on the Earth's temperature, developing a model that takes into account not only thermodynamics but also the important convective processes that occur inside the atmosphere due to temperature gradients. Although very simplified, being an essentially "local" theory, Manabe's first model led to the quantitative calculation of the temperature increase caused by the doubling of the CO_2 concentration, the so-called climate sensitivity. Manabe's calculation, then refined in a subsequent work to take the horizontal variations in a simplified topography into account, was that of an increase in temperature of about $2.5\text{ }^{\circ}\text{C}$, in surprising agreement with the current estimates.

Klaus Hasselmann, in the mid-1970s, well ahead of his time, laid the foundations for the analysis of climatic phenomena through the theory of stochastic processes. The starting point is the observation that climatic dynamics are characterized by an extreme degree of complexity, being described by a multiplicity of time scales and scales of different lengths. Inspired by the theory of Brownian motion, Hasselmann applied the theory of stochastic processes to climatic phenomena, considering fast meteorological variations as random "noise", whose properties could determine much slower variations of the climate, that is the "signal" to be detected. On the basis of this approach, since the late 1970s, Hasselmann has studied the problem of how to quantify climate change from an observational-experimental point of view, laying solid statistical foundations to identify an anthropogenic effect. Hasselmann's work covered many different areas, from the more theoretical aspects concerning the description of stochastic processes to the organization of satellite remote sensing campaigns [4,5].

Giorgio Parisi is, among the three winners, the physicist who highlighted the most fundamental aspects of the physics of complex systems, with particular reference to the behavior of disordered systems.

3. Climate Models and Their Complexity

Climate models are numerical representations of the climate system that furnish valuable tools for understanding climate and for anticipating future behavior changes. Numerical methods may vary from model to model depending on whether the emphasis is on the accuracy of the calculations or on their efficiency. Parameterizations are used to represent the transfers of water, energy and momentum and other significant parameters and are often universal for a specific model. The complexity of a model is defined as the number of climate processes taken into account. The first climate models developed in the 1970s represented only the atmospheric component. The models evolved rapidly and were able to include all four components in the late 1990s. There are very simplified, one-dimensional models based on the terrestrial radiative balance, which simulate only the global average temperature, not regional disparities. On the other hand, the most complex models represent the entire carbon cycle, and allow to estimate the carbon exchanges between the different components. Between these, there is a whole range of models of increasing complexity developed for specific applications. With the level of complexity, one also introduces more degrees of freedom into the system. This complicates its calibration

and validation, sometimes at the expense of the robustness of the model. It is therefore important that the calculation cost be reasonable in order to make many tests [6,7].

4. Comments on Articles

The Special Issue is constituted by eight contributions.

In the article titled “Suitability Assessment of Weather Networks for Wind Data Measurements in the Athabasca Oil Sands Area” the goal was to determine an optimal network for the wind data measurement that could sufficiently represent the wind variability in the area of the Athabasca Oil Sands Area (AOSA) in Alberta (Canada). The available historical data records of the meteorological stations in the three AOSA networks were used, i.e., the water quantity program (WQP) for monitoring oil sands (OSM) and edge sites (ES) and meteorological towers (MT) of the Wood Buffalo Environmental Association (WBEA) of the air program [8].

In the article titled “Coastal Wave Extremes around the Pacific and Their Remote Seasonal Connection to Climate Modes”, the authors propose a new “2-way wave tracking algorithm” to evaluate and quantify open ocean origins and associated atmospheric forcing patterns of cost wave extremes across the Pacific Basin for the period 1979–2020. A strong interconnection was found between tropical and extra-tropical regions with approximately 30% of coastal extremes in the tropics originating at higher latitudes and vice versa [9].

The article titled “Testing the CMIP6 GCM Simulations versus Surface Temperature Records from 1980–1990 to 2011–2021: High ECS Is Not Supported”, reports that the latest generation CMIP6 global circulation models (GCMs) are currently used for climate and future changes and to govern policy makers, but they are very different from each other; for example, their sensitivity to equilibrium climate (ECS) ranges from 1.83 to 5.67 °C (IPCC AR6, 2021). The authors test the performance of 38 CMIP6 models to reproduce the observed surface temperature changes from 1980–1990 to 2011–2021 in three temperature records: ERA5-T2m, ERA5-850mb and UAH MSU v6.0 Tlt [10].

In the article titled “Functional Data Visualization and Outlier Detection on the Anomaly of El Niño Southern Oscillation”, in order to study the Southern El Niño Oscillation (ENSO), the author adopted the theory of functional data analysis by representing a multivariate ENSO index (MEI) as functional data in climatic applications. The results suggest that the outliers obtained from the functional plot are therefore related to the El Niño and La Niña phenomena [11].

The article titled “Synoptic–Dynamic Patterns Affecting Iran’s Autumn Precipitation during ENSO Phase Transitions” reports the comparison of the effect on autumn precipitation on Iran during two types of phase transitions El Niño–Southern Oscillation (ENSO) from the point of view of anomalies in the flow of wave activity and in the pressure at sea level along the Atlantic–Mediterranean storm route, as well as precipitation. Using the Oceanic Niño Index (ONI), two transition phases of ENSO have been identified: from El Niño to La Niña and also from La Niña to El Niño [12].

The article titled “On the Breaking of the Milankovitch Cycles Triggered by Temperature Increase: The Stochastic Resonance Response” discusses the effects provided by a global temperature increase on climate behavior, as inferred by both applying the stochastic resonance interpretative model for climate and WT data analysis. In particular, a Milankovitch-cycle-breaking scenario induced by a triggering temperature increase, independently from a peculiar temperature trend, is forecasted by the climate stochastic resonance model. Numerical simulations for increasing planet temperatures have been performed. The simulations’ outcomes beget the following scenario: starting from the resonance condition, the Earth’s temperature increase boosts a transition towards a chaotic regime, where the Milankovitch cycles disappear. In this framework, the obtained results justify, on short time scales, the registered intensity increase of extreme meteorological events [13].

The article titled “Differences in the Reaction of North Equatorial Countercurrent to the Developing and Mature Phase of ENSO Events in the Western Pacific Ocean” studies

the changes in the Northern Equatorial Countercurrent (NECC) in the Western Ocean over 25 years (1993–2017) using satellite data provided by the Copernicus Marine Environment Monitoring Service (CMEMS) and the Remote Sensing System (RSS). It emerged that, at first, the NECC strengthened or weakened in every event of El Niño (La Niña) [14].

In the article titled “Kelvin/Rossby Wave Partition of Madden-Julian Oscillation Circulations” the authors divide the MJO circulations into Kelvin and Rossby wave components for three data series. These results support the use of a system of linearized equations on a basic rest state for the Kelvin wave component of the MJO circulation, but put it to use for the dubious component of the Rossby wave [15].

5. Conclusions

Recent years have seen a huge increase in the degree of emphasis on climate issues as a whole and in the level of attention paid to climate change modeling in particular. This is mainly due to the fact that finding practical, workable and cost-efficient solutions to the problems posed by climate change has become nowadays a global priority, and to the existence of stronger and stronger links among government, non-government organizations and general public. The present Special Issue deals with problems, approaches, challenges, and study cases related to climate change with a view to facilitating knowledge diffusion and networking between people, stakeholders, and research organizations.

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