CS1. Dr. Mihaela CAIAN

CLIMATE MODELLING AND PREDICTION

ABSTRACT HABILITATION THESIS

Bucharest 2023

Weather prediction has always been an element of great necessity for carrying out activities and protecting ecosystems, so that constant research efforts have been made in understanding, attributing, identifying mechanisms of variability in order to estimate future changes. A real scientific progress was the development of numerical models that allow solving complex discretized equations that govern the evolution over time of the climate system, a thermo-hydro-dynamic system and the interactions between its component sub-systems.

Although paleoclimate reconstructions (observations and modeling) indicate a stable climate for the past, the climate of the last decades shows a steep warming, significant after 1980, as well as the rise of the sea level, the reduction of the snow cover, together with significant increases in the concentrations of greenhouse gases in the atmosphere. At the same time, unprecedented changes are observed in extreme events (intensity, frequency, persistence) with major impact on ecosystems, life and various sectors of activity. The problem of attribution of global warming and future changes in response to developments in anthropogenic forcing has been advanced to the level of simulation, understanding and future predictiona/ projections **only thanks to unprecedented numerical modeling** and computational **developments**. The scientific community is making sustained efforts to continuously measure, identify the evolution and attribute causality of these changes as well as to estimate the potential climate response for different time horizons under emission, radiative forcing and more recently adaptation scenarios.

The habilitation thesis with the title "Climate modeling and prediction" presents the synthesis of the activity, results and contribution made in the field of climate modeling and prediction throughout the entire scientific research activity before and especially after obtaining the doctorate in the field of Meteorology - Numerical Modeling. The doctoral thesis with the title "Maille variable ou domain limte: quelle solution pour la modelisation a echelle fine?" (Variable grid or limited domain: what is the optimal solution for modeling the atmosphere at fine scales ?") was held in a public examination on November 23, 1996 in Toulouse, France, Paul Sabatier University, in the presence of an International Examination Commission made up of seven experts in the field. From obtaining my doctorate until now, I have been involved in scientific research activities with basic directions: **research in numerical modeling and development of climate system models**: atmospheric (Aladin model), regional climate (RegCM model) and global climate (UK MetOffice, IFS, EC-Earth models), also **the research**

direction in the field **of climate prediction and projection scenarios** through deterministic modeling and through the development of conceptual models and also research towards **the development of applications** of the results, anchored in the current climate reality.

The results of these developments and theoretical and applied research have been **valued nationally and internationally.** Thus, the ***theoretical results*** obtained in these research directions were valued, being included in the new generations of climate models (e.g. in the recent version of the EC-Earth model, used in the creation of the latest CMIP6 climate scenarios). Also, other theoretical results obtained were included as new prediction methods for example in the deterministic decadal prediction (anomaly initialization methods in coupled climate systems for the 10-30 years range decadal predictions, implemented and used in the EC-Earth Consortium model) or included as new conceptual prediction methods. The developed conceptual models led to the identification and validation of relevant prognostic indicators for the physical mechanism that pre-condition the development of physical processes leading extreme climate events. They are currently used in current meteo-hydrological work (floods, late blizzard, drought, genotyping and optimal crop dating for the current agro-season, etc.). Regarding the need for valorization of the ***applied results***, we have developed and implemented several integrated numerical systems based on forecast products and climate data and scenarios, in support of some key areas of the activity sectors (e.g. agro-climate, air quality, coastal actions, integrated systems, etc., described in the thesis).

The work presented as a habilitation thesis describes the professional, academic and scientific achievements to date (2023), and perspectives, in the main directions of research activity, results that are embodied in a number of 28 publications in journals indexed on the Web of Science website with ISI impact factor (16 articles in the red zone, and 1 first-author paper cited in IPCC 2022). The utility of these results is reflected by the citation of articles in over 400 scientific papers cited in the Web of Science database with ISI impact factor. Some of the research results are published in 3 specialized books and in specific chapters in other 2 volumes (book and proceedings) as well as in more than 15 internal Notes in international journals (Newsletter -research, Technical Reports) from abroad. A number of 68 scientific papers are mentioned on academic websites.

I summarize here the research contributions on the modeling and prediction of the climate system processes at **the global scale and regional scale** (detailed in the paper in **Part I**, Chapter 1 and Chapter

2, respectively). For each of the two spatial scales I present in a similarly structured way, results in climate modeling and in prediction (theoretical contributions and developments). At the end of the results I summarize also the contributions towards the **development of applications** for the exploitation and use of the results (Chapter 3).

The research and development activity in **climate modeling and prediction on a global scale** (Chap. 1 in the paper, 1.1.4 respectively 1.2.4) includes both atmospheric process models (AGCM general circulation models) and interactively coupled models of climate sub-systems (hydrosphere, lithosphere, cryosphere, biosphere) and other sub-components with a determining role (ESM coupled models "Earth system model", Fig.1). ESMs have a very high degree of complexity and allow the inclusion of the multitude of non-linear interactions between sub-systems, the only way by which a high degree of accuracy of the solution can be obtained.

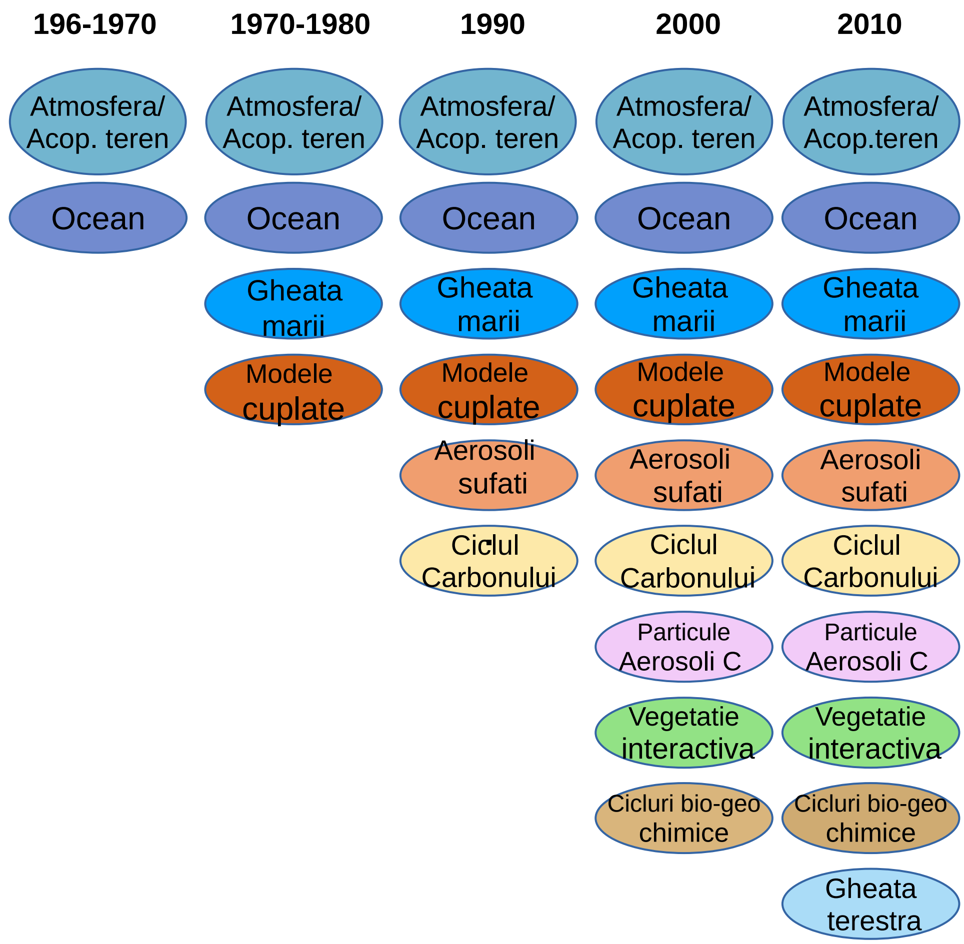

Fig.1 The sub-components and the evolution of the global modeling through the coupling of new sub-components of the climate system.

First t***heoretical contributions in global-scale modeling*** were achieved in the modeling of very fine spatio-temporal scales when, in order to increase the resolution of the AGCM, a new mathematical solution, the variable grid, is explored. In this solution, the system of physico-mathematical equations of the atmospheric flow is represented in a new topology of the sphere, a conformal function transform of the real spherical topology, whose factor (called "stretching coefficient", C) refines the resolution in -a "polar" region of interest, but instead widens it (grid expansion) to the opposite "pole". The mathematical analysis carried out identified the theoretical basis for explaining the physical behavior of the simulated response, namely, it was shown that in a conformal topology, the stretching coefficient is limited because the convergence in the variable grid becomes mathematically non-uniform (point-dependent, through the coefficient of "stretching"). Thus the truncation errors become non-orthogonal to the component brought back into the real physical space, with an accumulation of (non-physical) energy from the large scales to the smallest scales of the energy spectrum. Consequently, the slope of the energy cascade in the turbulent spectrum (e.g. k~ - 5/3) becomes a function of the coefficient C.
In addition, another source, physical, which theoretically limits the application to a small-moderate value of the stretching, was highlighted in relation to parameterized physical processes (i.e. processes not resolved by dynamic equations), especially those in the boundary layer. Thus the similarity theory, as an example, in order to lead to consistent relationships with the transformed dynamical system (without energy accumulations), must in turn include "C" in the Buckingham theorem used in dimensional analysis for calculating the exponents for the transfer functions in the layer limit. Energy accumulations were already visible in all numerical simulations carried out in climate modeling centers (France, IFS-ECMWF), and this analysis identified the mathematical reasons that impose the limitation of the C coefficient, thus guiding the choice of practical solutions in operational numerical weather modeling of the atmosphere. Currently the C coefficient used in opperations in climate modeling centers (e.g. the Arpege model used in this research) does not exceed 3.5.

Other ***theoretical contributions in global modeling*** were made in the study of the coupling between the stratosphere and the troposphere (S/T) where it was highlighted how this is modified following volcanic eruptions, when a large amount of aerosols is injected into the atmosphere. It has been highlighted how, apart from the radiative effect, the S/T coupling is affected by (observed) dynamical changes in the circulation, with implicit regional response in the lower troposphere. These results (obtained through sensitivity simulations with the global UK-model) contribute to the understanding and estimation of the impact of volcanic eruptions, 1-3 years after the event and to the improvement of the physical-dynamic interaction in the models.

In the study of atmospheric **physical processes**, ***theoretical contributions*** were made in the simulation and explanation of the dry high convection mechanism, which led to the improvement of the deep convection parameterization scheme in the EC-Earth global model, and the correction of the previously existing bias in representation of the diurnal cycle of convection (with impact in the prediction of precipitation extremes). Another important process for climate variability, the Madden-Julian oscillation (MJO, 30-90 days) was studied by implementing the "aqua-planet"-IFS version in the EC-Earth global model, an idealized version of planet completely covered by water. This study made fundamental ***theoretical contributions*** to the analysis of the dependence of the MJO oscillation on the intensity and position of a thermal anomaly at the surface of the Equatorial Ocean and allowed to improve the modeling of this process. These theoretical results have already been included and accounted for in the definition of the new CMIP6 models generation (that improve the CMIP5 models, “Coupled Model Intercomparison Project Phase 5”).

In terms of theoretical ***contributions to climate prediction*** on a ***global scale***, I carried out a research activity 2010-2017 in the newest field, pioneering at that time, namely decadal prediction, research initiated in an international cooperation, in which personally I dealt, with original results, in research and development on the problem of initializing these predictions. These extended forecasts can be very useful in socio-economic development and adaptation actions, in the context of the current climate trend. Personal ***theoretical contributions in global prediction*** (Chap. 1, 1.2.4) concern the identification of a new, coherent phase initialization method for coupled systems (ocean-atmosphere-sea ice) initialized by the anomaly method. This method ensures the correct propagation of the slow, wave-propagating predictive signal, thus increasing the score of the decadal predictions. The prediction system thus initialized for the Ec-Earth model was used in the production of the first decadal prediction simulations (currently performed bi-annually) and then in the production of the decadal prediction database of CMIP5, available and usable at global level, for any research activity. Also are described other theoretical contributions in decadal prediction through a series of researches for the optimization of prediction sources, such as: optimization of the representation of the Quasi-biennial QBO oscillation

(~28 month period) in the gravity wave parameterization scheme for fine resolutions, inclusion of zonal ozone variability in the forcing data—for which we have demonstrated a notable impact on tropospheric extremes in extended predictions.

Another important ***theoretical research*** in the field of ***climate projections*** was related to the analysis of singular points **("Tipping points") of the climate system.** We investigated the occurrence and the mechanism of the appearance of "tipping-point" characteristics for the El-Nino phenomenon, using "rump-up", "rump-down" scenarios of forced radiative heating (200 years) followed by stagnation of the forcing and warming decrease (200 years), in order to identify if the climate system returns to its initial state or there is a risk of an irreversible transformation, in which tha system remains in a new equilibrium state. We showed the preponderance of Modoki-type El-Nino and proposed a mechanism to explain significant changes in its variability in the system thus forced.

Contributions to the ***development of global models***: These theoretical results on climate and global climate system, modeling and prediction, obtained and presented in the thesis, were valued in international modeling consortia and considered in defining the new generation of CMIP6 models (improving the generation of CMIP5 models), in which we actually participated by including these upgrades in the EC-Earth global model code as well as in the climate scenario simulations (CMIP5), currently present in the CMIP5 database, but also in the decadal prediction database.

In the same structure as before for ***global modeling,*** I summarize below the results presented in the paper (Chap. 2) for the ***regional scale***, successively, in the field of ***modeling*** and then of ***climate prediction*** (theoretical contributions and developments). These regional researches were oriented with a focus on Romania and the thesis presents new results both in understanding and predicting regional climate change especially extremes in the area of our country.

Theoretical contributions in ***regional scale modeling*** concern the development and occurrence mechanisms (with the identification of predictive elements) of some regional extreme events in Romania. The analyzes were carried out through numerical sensitivity simulations with regional climate models and the results led to the proposal of conceptual models, which were validated on observational data of the extreme event. The utility of these conceptual modeling of a phenomenon lies in the fact that they allow the derivation of large-scale prognostic indicators ("proxies" of the mechanism) that pre-condition the extreme event and that have a high degree of predictability. They thus provide physically consistent prognostic information where the resolution of the models is practically never good enough (e.g. local extremes). Conceptual modeling led for the purpose of understanding and predicting extreme regional phenomena, included: conceptual modeling of teleconnection mechanisms that leads to extreme anomalies in the frequency of cyclonic trajectories over SE Europe - Romania; conceptual model for predicting intra-annual NAO variability (as a function of regional persistent sea ice anomalies from the previous year); conceptual model for identifying the weather context and the mechanism that pre-conditions the occurrence of floods on a sub-regional scale in Romania; also for the identification of a physical-dynamic mechanism responsible for the evolution (amplification/decrease) of those extreme Mediterranean cyclogenesis causing significant annual damage and late blizzards in the Eastern and Southern areas of Romania (composite indicators, function of the stability of the Polar Jet and the temperature anomalies of the Mediterranean Sea and the Black Sea were identified). These studied mechanisms concern important elements of extreme, intra- and inter-annual variability in the European region, having a major social and economic impact.

The most important ***theoretical contributions*** in ***climate prediction at the regional scale*** include: the implementation of the first regional climate modeling system for Romania (Grant of the Romanian Academy), by: including the coupling of the RegCM model with a model for the Black Sea, fitting the ozone profile with local measured data, implementing Genetic Algorithms for the optimization of the physical parameterization settings in the model for the Romanian area, etc. Another contribution is the implementation of the first chain of numerical forecast models for downscaling the month-season interval, of fine resolution, for Romania (the RegCM model), currently run in operational seasonal forecast chain in ANM (10km) for the regionalization of the ECMWF/SEAS5 global forecasts (~ 60km).

Contributions to the development of regional models: were brought within the framework of international cooperations (at ICTP), involving some developments to the regional climate model RegCM such as the inclusion of the Lambert projection in the model (which increases the score of simulations for mid-latitudes), the adjustment of the parameterization scheme of boundary layer processes (transfer functions).

I conclude the summary of the results obtained in **regional climate and prediction modeling** with recently implemented **application developments** for the exploitation of the obtained results (developments presented in Chapter 3). Among these, I mention the realization of the ***first multi-model regional climate scenarios*** of a very fine scale (5 km) for Romania (RCP scenarios), as well as extending these scenarios to support in decision-making and management actions (through land cover projected change scenarios e.g. according to VOLANTE projections), management measures that are required more and more firmly in the current period and in the near future. Another recent application is the implementation of new ML/Genetic Algorithms techniques in a hybrid mode (with deterministic modeling) in order to identify optimal future crop genotypes and optimal planting conditions (date-day, fertilization, etc.), for the time horizon 2050, in the context of climate change, but also for seasonal forecast, for the main agro-regions in Romania. The method was implemented and can be exploited interactively (system loaded in the EERIS platform, https://eeris.eu/) online by decision-makers, farmers. The results of the numerical seasonal predictions are further applied for the forecast of drought conditions, coastal parameters for the Black Sea (a coupling between the RegCM model - the POM sea model - the POMVal wave spectral model was implemented), as well as in long-term estimates of average air quality conditions (through Chimere-ECMWF/SEAS5 model coupling).

In the Work presented as a habilitation thesis, the **didactic activity** at various national and international Universities is also presented (in **Part II**). I held series of courses and seminars at national and international Universities (UB (Numerical Modeling, year III, and doctoral years), ATM (Special Mathematics and Mathematical Analysis, year II), UPB (Climate Modeling, invited course, year III), Imperial College -UK (Computational Physics, year III 2000-2003)) and postgraduate courses (Romatsa (Atmospheric Dynamics, Numerical Modelling, Atmospheric Instabilities), SNM (Atmospheric Dynamics, Numerical Modelling), SMHI-Rossby Center -Sweden (Climate Modelling, Climate Change, 2012-2018)). During this time I have contributed to the guidance or examination of several doctoral theses in the country (UB) and outside the country (Sweden).

Regarding the **immediate perspective,** the paper (in **Part III**) details the Development Plan of own career (including didactic and academic) in the next period and future research directions. These include innovation work, guidance and expertise transfer alongside PhD students. Of these, priority are directions that address the most urgent, current problems of the climate crisis that already affect us and for which I am still fully involved. Thus, I will focus on bringing new contributions to the understanding of the mechanisms of amplification and prediction of **regional climate extremes** (Romania) in the context of a climate in transition, using numerical simulations with very fine resolution climate models and theoretical, conceptual modeling. Another particularly necessary direction will be the realization of **new priority regional climate scenarios** of socio-climatic risk (e.g. agro, forests, coastal area, mountain) using state-of-the-art climate modeling with the aim of estimating the dynamics of climate risk areas in the near future, in the context of climate change. In this sense, a main focus will be the identification of the potential context and climatic ecosystems with characteristics of irreversibility **("tipping-point")** and the quantification of associated probabilities.

Also here, the expansion towards mixed regional scenarios is required, by including in the numerical simulations, **regional management scenarios** (optimization / adaptation / mitigation) in relation to the Green Deal 2050 goal, with the aim of quantifying the climate response to these actions and find optimal mitigation/adaptation solutions. In terms of climate prediction there are two main innovation objectives. They concern the increase of **regional extended prediction** performances in the already advanced month-season prediction level, but especially regarding the actual newest predictive approach, the decadal prediction. Especially we can contribute to the improvement of these estimates for the region of our country, through regional modeling techniques that initialize as precisely as possible the relevant (slow) predictive signal, through demonstrated teleconnections, for our region (e.g. Black Sea, Mediterranean, North Atlantic Ocean, ice Arctic, pressure modes with significant teleconnection, land cover, etc.). Prediction simulations and regional modeling climate scenarios have been developed and carried out so far only in the research group I coordinate, which gives me a major motivation for cooperation and involvement of new PhDs in this field. These (seasonal, decadal) are extremely necessary at this moment and have aroused a growing interest, priority lately at the level of users and decision-makers, according to the analysis-survey carried out in the framework of the National Climate Change Strategy project (2022).

An immediate objective of the future research, but also didactic activity, is the implementation and investigation of **new "data-modeling" techniques** in climate prediction and modeling, e.g. artificial intelligence (AI), machine learning (ML) in parallel or hybridly with classical deterministic modeling, for a series of problems, e.g. from the sub-regionalization of climate predictions or scenarios (to increase accuracy in the representation of local extremes), to the simulation of explicit physical parameterizations through AI solutions, to theoretical problems of cause-effect attribution or to the use in optimization studies (with potential major impact for planning sectoral against disasters or for adapting to climate change).

Regarding the development perspective in the university didactic process, a particular objective is the inclusion of interactive aspects through relevant practical applications, of numerical modeling, of theoretical concepts, analysis, simulation and solving problems anchored in the current climate reality, that could contribute to the acceleration of the innovative process. Another didactic focus will be the continuous updating of knowledge at the level of the most recent and rated publications in the field of research approached by doctoral students, to ensure a high level of professional training. In particular, an emphasis will be placed on encouraging the immediate publication of original results obtained by PhD students, in journals with a high impact factor (web-of-science). A priority objective as PhD supervisor will be to expand national and international collaborations with research groups, in the proposed directions as well as in inter-disciplinary fields. I propose to intensively support the involvement of doctoral students in research projects and cooperations, particularly useful in training and development. Within them, the practical application of the results is important, e.g. conducting regional climate scenario or prediction projects down to the processing of the results as a scientific basis for new climate services or integrated services (e.g. of the "Digital twins" type), which can lead to significant, scientifically based benefits.