Сучасний Стан Моделювання Клімату

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Current State of Climate Modelling

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***Анотація*—У даній статті досліджується встановлена ієрархічна класифікація кліматичних моделей; розглядаються області застосування, переваги та недоліки різних типів моделей; представлено короткий виклад поточних тенденцій щодо удосконалення підходів до моделювання клімату.**

***Abstract*—This paper explores the established hierarchical classification of climate models; considers areas of application, advantages, and disadvantages of different types of the models; presents a summary of current trends for improvements in approaches to climate modelling.**

Ключові слова—зміна клмату; кліматична модель; модель загальної циркуляції; сполучення моделей

Keywords—climate change; climate model; general circulation model; model coupling

I. INTRODUCTION

Understanding the Earth's climate is crucial for addressing environmental challenges and ensuring planetary sustainability. By providing insights into the inner workings of the climate system, the study of climate allows us to predict and mitigate unwanted impact on ecosystems, economies, and human societies. Climate models serve as the primary tool for this task, enabling scientists to simulate complex interactions within the Earth’s climate system, assessing human contribution to the environment, and ultimately influencing decision-making processes to combat dangerous consequences of the climate change. Improving climate models is therefore the key direction of development in climate science.

Accuracy is not the only property of the climate models which researchers are interested in; in some cases, better computational performance or comprehensibility of the model can be more beneficial. Unfortunately, these three properties cannot be achieved equally well for any model. This mutual exclusivity has led to development of different approaches to climate modelling, depending on the desired balance of the three properties for the end applications.

This paper explores the established hierarchical classification of climate models, considers areas of application, advantages, and disadvantages of different types of the models, and presents a summary of current trends for improvements in approaches to climate modelling.

II. CLIMATE MODEL TYPES AND THEIR FEATURES

All variety of existing climate models is commonly divided into three main categories, listed in order of increasing complexity:

- energy balance models (EBMs),
- earth systems models of intermediate complexity (EMICs),
- general circulation models (GCMs).

A. Energy balance models

Energy balance models are considered the simplest among the three categories. Their common and key feature is utilization of the Stefan–Boltzmann law for building an equation that balances incoming solar energy and outgoing energy radiated by the Earth. Incoming solar energy is calculated based on the Earth’s cross section area and the solar constant; outgoing energy is calculated from the Stefan–Boltzmann law using the Earth’s surface area. Equating incoming and outgoing energy yields and equation with a single unknown variable T, which denotes the Earth’s averaged surface temperature at equilibrium.

In addition to the variables listed above, EBMs can be designed to account for the reflectivity of the Earth's atmosphere and partial absorption of outgoing radiation affected by ice caps, clouds, atmospheric aerosols, and greenhouse gases by introducing additional parameters to the equation. Beside zero-dimensional models, one-dimensional EBMs can also be constructed, in which case the temperature T is averaged over separate latitudes, rather than the whole globe [1].

The main variable of interest in EBMs is the averaged Earth's temperature T. These models are useful for calculating T at equilibrium under given assumptions about the Earth's state (albedo, greenhouse effect factor, etc.), as well as determining the nature of the change of T when energy imbalance takes place. Due to their relative simplicity, EBMs can be analysed mathematically, and many variants of EMBs have a closed-form solution for T. These models are also well-suited for climate sensitivity predictions.

The main drawback of EBMs lies in their inherent inability to capture localized state of the Earth's climate. Complex processes, such as oceanic currents or cloud formation, cannot be modelled with reasonable accuracy using EBMs, and can only be represented as some empirically determined parameters that convey their average effect on the global temperature.

B. Earth systems models of intermediate complexity

Earth systems models of intermediate complexity, unlike EBMs, allow for incorporating a broader range of climate system components with more detailed modelling of their internal processes; main examples of such components include atmospheric dynamics, ocean circulation, and sea ice dynamics. EMICs typically feature 2- or 3-dimensional subdivision of the Earth's surface using grid system, although some of the climate components may be represented in one-dimensional space or parametrised. This enables EMICs to capture regional features of climate.

From the perspective of modelling approach, EMICs closely resemble global circulation models due to utilization of the grid system. However, because of the simplified representation of their component processes and lower spatial and temporal resolution, EMICs are poorly suited for working with high-frequency variations of the climate system, as well as highly localised climate features. They are also complex enough compared to EBMs, causing limited to no opportunities for traditional mathematical analysis.

The principal strength of EMICs lies in their low computational costs, as opposed to GCMs. This allows EMICs to be efficiently used for long-term simulations (both fore- and hindcasts), evaluation of other models through coordinated intercomparisons, or verification of GCM predictions.

C. General circulation models

General circulation models are the most complex, state-of-art models used in climate science. Similar to EMICs, these models feature 3-dimensional grid subdivision of the Earth's surface, but with substantially finer spatial and temporal resolution. GCMs aim to account for as many climate processes and parameters as possible; simulational approach is strongly preferred over parametrisation when modelling component processes in GCMs. This results in the best possible precision among all types of models, which comes at the price of rapid increase in computational costs, up to requiring supercomputers to run simulations in case of the most advanced models.

Being on the complex end of the hierarchy of climate models, GCMs (specifically, coupled atmosphere-ocean GCMs) are currently viewed as the most promising tool for understanding, simulating, and predicting the state of the Earth's climate system by major climate and meteorology institutions. Despite their precision, achieving good accuracy is one of the main challenges of developing GCMs due to the lack of complete understanding of internal nature of some processes and feedback mechanisms – one of the notable examples being cloud forming.

III. PERSPECTIVES

The general consensus regarding the current state of climate modelling is that the primary obstacle for improving climate models is caused by the lack of computational power. The demand for improvement, in turn, is mostly extensive, and consists of increasing the spatial resolution of models; increasing the realism of the climate system within models; and increasing the number of individual model runs [2]. Special attention is given to refining spatial resolution of the models, as it would allow to better predict extreme weather events, which are typically generated by processes operating at kilometre scales [3]. Such resolution has already been achieved for regional weather models, but for climate models it remains too computationally expensive. The primary solution to this problem is seen in distributed computing and international cooperation between climate institutions.

Among intensive changes, the most prominent trend in the recent decade has been exploring possibilities of creating global climate models with variable scale [4]. This trend is mainly driven by raising understanding that the benefits of high spatial resolution of regional climate models are outweighed by the lack of detailed interactions between the modelled region and the rest of the globe. The Met Office Unified Model is considered to be the world-leading climate model of such type.

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