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Review Article

Evolution and prospects of Earth system models: Challenges and opportunities

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Abbreviations: 3SMAC, Three-dimensional Seismological Model; ACCESS-ESM1–5, Coupled Large-scale Aerosol Simulator for Studies in Climate (CLASSIC), HadGEM2-ES, CABLE2.4, GFDL MOM5.1, World Ocean Model of Biogeochemistry and Trophic-dynamics, CICE 4.1; AIMES, Integration and Modeling of the Earth System; AIS, Antarctic Ice Sheet; ALADIN, Aire Limitée Adaptation Dynamique Développement International; ALARO-0 (RMIB-UGent), ALADIN and AROME (Application de la Recherche à l'Opérationnel à Meso-Echelle) combined model; ARPS, Advanced Regional Prediction System; AWI-CM-1-1-MR, Alfred Wegener Institute Climate Model-1-1-Marine Research; BCC-CSM2-MR/HR, BCC-AGCM3-MR/HR, BCC-A VIM2.0, MOM4-L40; BNU-ESM, Earth system model of Beijing Normal University; CAMS-CSM1–0, ECHAM5_CAMS, CoLM 1.0, MOM4, SIS 1.0; CanESM5, CanAM5, NEMO, CMOC, CanOE; CCSM4, Community Climate System Model version 4; CESM2, Community Atmospheric Model version 6 (CAM6), MOZART chemical mechanism, Community Land Model version 5 (CLM5), Community Ice Sheet Model version 2.1 (CISM2.1), Parallel Ocean Program (POP), BEC, CICE 5.1.2; CLMcom, Climate Limited-area Modeling Community; CMIP5, Coupled Model Intercomparison Project phase 5; CNRM-CM6, ARPEGE-Climat Version 6.3, NEMO: Nucleus for European Modeling of the Ocean version 3.6 (OPA); CNRM-ESM2, TACTIC_v2, ARPEGE-Climat Version 6.3, REPROBUS-C (v2.0), SURFEX v8 modeling platform, NEMO: Nucleus for European Modeling of the Ocean version 3.6 (OPA), Pelagic Interaction Scheme for Carbon and Ecosystem Studies model volume 2 version trace gases (PISCESv2-gas); COSMO, Regional climate model COSMO-CLM; cpl7, Version 7 coupler; CRCM, Chinese Regional Climate Model; CRCM5 (UQAM), Canadian Regional Climate Model, version 5; CRUST, A global crustal model; DICE, Dynamic Integrated Climate Economy model; E3SM, EAM, ELM, MPAS, MPAS-O, MPAS-SI, MPAS-LI; EC-EARTH3, Integrated Forecasting System (IFS), HUSESEL, NEMO 3.6 (Nucleus for European Modeling of the Ocean version 3.6), LIM3, LPJ-GUESS, TM5; ECMWF, European Center for Medium-range Weather Forecasting; ECMWF-IFS, HRES, ENS, NEMO (LIM-2), HRES-WAM, ENS-WAM; ECPC/ECP2, Experimental Climate Prediction Center; EMIC, Earth System Models of Intermediate Complexity; ESM, Earth System Model; ESS, Earth System Science; Eta (INPE), Eta Model; EWBM-A, Energy and Water Balance Model; FGOALS-f3, FAMIL, SAMIL, LICOM3, CLM4, CICE4; FIO-ESM v2.0, CAM5, CICE4, POP2, MASNUM, CLM4; GCM, Global Climate Model; GEM-LAM, Global Environmental Multi-scale - Local Area Model; GFDL-ESM4.1, GFDL-AM4.1, GFDL-ATMCHEM4.1, GFDL-LM4.1, GFDL-OM4p5, GFDL-COBALTv2, GFDL-SIM4p5; GISS-E2, SEA06, TCAD/TCADI, NINT, HYCOM; GLP, Global Land Project; GPS, Global Positioning System; HadGEM3, Hadley Centre Global Environment Model version 3; HEI, Human–environment interaction; HIRHAM5 (DMI), HIRHAM Regional Climate Model; HIRLAM, High Resolution Limited Area Model; IA, Integrated Assessment; IA-ES, Integrated Assessment-Earth System; IAM, Integrated Assessment Models; IBP, International Biological Program; ICSU, International Council for Science; IGBP, International Geosphere Biosphere Programme; IGY, International Geophysical Year; IITM-ESM, GFS, Noah LSM, GFDL-MOM4p1, Sea Ice Simulator (SIS); IM, Integrated Model; INMCM, Institute of Numerical Mathematics of Russian Academy of Sciences Climate Model; InSAR, Interferometric synthetic aperture radar; IPCC, Intergovernmental Panel on Climate Change; IPSL-CM6A, LMDZ6A, ORCHIDEE surface model, NEMO: Nucleus for European Modeling of the Ocean version 3.2 (OPZ), NEMO: Nucleus for European Modeling of the Ocean (TOP/PISCES), Louvain La Neuve Sea Ice Model version 3; LAIC, Lithosphere–Atmosphere–Ionosphere Coupling; LiDAR, Light Detection and Ranging; LITHO1.0, An Updated Crust and Lithosphere Model; LTER, Long Term Ecological Research; LUCC, Land Cover Change Program; MCT, Model Coupling Toolkit; MEMS, Microelectromechanical Systems; MIROC6, SPRINTARS, MIROC-AGCM, MATSIRO6, COCO4.9; MIROC-ES2, MIROC-AGCM, CHASER (MIROC-ESM); ML, Machine Learning; MM5, Fifth-Generation Penn State/NCAR Mesoscale Model; MPI-ESM/HighResMIP, HAM2.3, ECHAM6.3-HAM2.3, HAM2.3, JSBACH3.20, MPIOM1.6.3, HAMOCC6; MRI-ESM 2.0, MASINGAR mk-2r4c, MRI-AGCM3.5, MRI-CCM2.1, Land Surface (HAL), MRI.COM ver. 4.4; NAM, North American Mesoscale Forecast System; NCEP, National Center for Environmental Prediction; NESM, ECHAM v6.3, JSBACH, Ocean PArallelise (OPA), CICE v4.1; NICAM16–9S, MACv2-SP, NICAM.16MATSIRO6; OASIS, Ocean Atmosphere Sea Ice Soil; OBLIMAP, A fast climate model-ice sheet model coupler; PNNLRCM, Pacific North West National Laboratory; RAMS, Region Atmosphere Model System; RCA4 (SMHI), Rossby Centre regional atmospheric climate model (RCA4); RCM, Regional Climate Model; RCM3, Third generation of the Regional Climate Model; RegCM, Regional Climate Model system; REMO, Regional Europe Climate Model; RIEMS, Regional Integrated Environment Modeling System; RSM, Regional Spectrum Model; STEP, Second Tibetan Plateau Scientific Expedition and Research; TP, Tibetan Plateau; UKESM, NEMO, CICE, TRIFFID, JULES, UKCA, MEDUSA, and BISICLES; WCRP, World Climate Research Programme; WRF-ARW, Advanced Research WRF; WRF-NMM, Nonhydrostatic Mesoscale Model WRF; YAC, Yet Another Coupler.

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ABSTRACT

Earth system models (ESMs) serve as vital tools for comprehensively simulating the intricate interplay of physical, chemical, and biological processes across the Earth system's diverse components. Here, we provide a brief overview of the historical development of ESMs and highlight key challenges posed by the intricate feedback mechanisms in the cryosphere, the nonlinear and long-term effects of the lithosphere, and the growing impacts of human activities for modeling Earth system. We then focus on the current opportunities in Earth system modeling, driven by the growing capacity for data-driven approaches such as machine learning (ML) and Artificial Intelligence (AI).

The next generation of ESMs should embrace dynamic frameworks that enable more precise representations of physical processes across a range of spatiotemporal scales. Multi-resolution models are pivotal in bridging the gap between global and regional scales, fostering a deeper understanding of local and remote influences. Data-driven methodologies including ML/AI offer promising avenues for advancing ESMs by harnessing a wide array of data sources and surmounting limitations inherent in traditional parameterization techniques. However, the integration of ML/AI into ESMs presents its own set of challenges, including the identification of suitable data sources, the seamless incorporation of ML/AI algorithms into existing modeling infrastructures, and the resolution of issues related to model interpretability and robustness. A harmonious amalgamation of physics-based and data-driven methodologies have the potential to produce ESMs that achieve greater precision and computational efficiency, better capturing the intricate dynamics of Earth system processes.

Although ESMs have made substantial progress in simulating the complex dynamics of Earth system's subsystems, there is still considerable work to be done. Prospects in the development of ESMs entail a deepened comprehension of pivotal subsystems, including the anthroposphere, lithosphere, and cryosphere. Adopting innovative technologies and methodologies, such as ML/AI and multi-resolution modeling, holds immense potential to substantially enhance our capability to anticipate and mitigate the consequences of human activities on the Earth system.

1. Introduction

The Earth system's dynamics span a broad spectrum of spatiotemporal dimensions, involving physical, chemical, and biological operations within and between the Earth system's sub-systems - such as the atmosphere, hydrosphere, biosphere, cryosphere, lithosphere, and anthroposphere. These complex, multi-scale dynamics, which can be chaotic and intricate, create a favorable climate that supports life and civilization. However, we lack a comprehensive understanding of these dynamics to ensure their continuous support for life and civilization, particularly when considering extremely small/large scales beyond conventional observations, as well as potential random natural disasters and climate change under increasing human impacts.

To numerically simulate and predict behaviors of the Earth system, Earth system models (ESMs) have been developed based on prior understanding of dynamic processes. These models are quantitative, discrete descriptions of Earth system processes executed by high-performance computers, typically built around numerical solvers of geophysical fluid dynamic processes occurring in the atmosphere and ocean. Parameterization schemes are employed to approximate unresolved physical processes, relying on heuristics, empirics, phenomenological laws, and closing assumptions. Additionally, models for other subsystems are often developed individually by domain experts and subsequently coupled with semi-resolved geophysical fluid dynamics to reveal their immediate and long-term impacts on the Earth system.

A growing trend in ESM development is to enhance numerical solver resolution and incorporate modules for previously oversimplified or neglected processes, aiming to develop a detailed and comprehensive "digital twin" of the Earth system capable of answering most climate-related questions (Li et al., 2023). However, increasing model resolution and complexity does not necessarily contribute to improved model accuracy if parameterization schemes are poorly tuned or if newly included physical processes are poorly coupled with existing modules.

ESMs, with their mathematical representations of physical, chemical, and biological processes' key components and properties, are designed to simulate pertinent elements of the Earth system (Bonan and Doney, 2018). Depending on their purpose, these models can vary significantly in complexity, and are used to illustrate the effects of climate change on various Earth spheres (Randall et al., 2019) and indicate how these aspects may change in the future. ESMs, which go beyond the scope of their predecessors, Global Climate Models (GCMs), are invaluable in improving our comprehension of intricate interactive processes within the Earth system, fulfilling scientific objectives of Earth system modeling, and informing policy-making (Prinn, 2013).

Although several review papers on ESMs exist (Flato, 2011; Prinn, 2013; Calvin and Bond-Lamberty, 2018; Giorgi and Gao, 2018; Steffen et al., 2020; Kawamiya et al., 2020; Zhou et al., 2022), these reviews primarily focus on the operation and future changes of the climate system (e.g., interactions, processes, and feedbacks shaping Earth's climate and determining its response to natural and human forcings) or the developments of specific ESMs (Prinn, 2013; Zhou et al., 2014; Giorgi and Gao, 2018; Kawamiya et al., 2020). Most of these reviews overlook the progress of geological processes in the Earth system, and only a few treat humans and their activities as physical and biogeophysical components in ESMs (Calvin and Bond-Lamberty, 2018; Steffen et al., 2020).

This review aims to address the challenge posed by increasing complexity in the Earth system and present new findings on interactions between different spheres previously absent in ESMs. It traces the history of ESMs, summarizes recent developments, and provides an in-depth review of data-driven modeling in Earth system science. Sections 2, 3, and 4 introduce the development, challenges, and opportunities of Earth system modeling, respectively, with concluding remarks and discussion in Section 5.

2. Development history of ESMs

The progressive accumulation of Earth system knowledge (Fig. 1), and consequently its modeling, originated from a specific set of equations that offered a deterministic representation of atmospheric and oceanic dynamics in the early 20th century (Abbe, 1906; Bjerknes, 1906). These models were then integrated and interacted with human dynamics, such as greenhouse gas emissions, land use change, and other decision-making behaviors, ultimately leading to the development of comprehensive ESMs (Shepelev, 1965; Checkland, 1976). The integration of these equations or their variants over spatial and temporal dimensions, using an initial state estimate, and the simulation of how these dynamics transfer mass, energy, and momentum among various Earth subsystems, laid the groundwork for contemporary Earth system modeling. This paradigm became feasible with the establishment of Earth observation networks and advancements in numerical analysis and computational techniques. The rapid expansion of computational power permitted the simulation of geophysical fluid dynamics at increasingly finer computational grids and facilitated the incorporation of process representations for Earth system components.

Contemporary ESMs include distinct modules for the ocean, atmosphere, land, land and sea ice, and biogeochemical cycles. Each of these modules represents a complex modeling system in its own right, with various parameterizations and the capability to run independently for specific applications. These modules can be configured in a variety of ways to create ESMs of varying complexity. A range of parameterization options is available to account for the cumulative effects of unresolved processes in the models, such as cloud formation, radiation, planetary boundary layers, and land surface processes. By combining the aforementioned components, forecasts are routinely carried out by numerous operational forecast centers and research institutes worldwide. The simulation outcomes supply updated predictive information for short weather ranges extending to the climate range. In the following section, we briefly highlight the milestones in the evolution of ESM development.

The progression of ESMs is rooted in conceptualizations of the Earth, aiming to comprehend the Earth system. This process began with the development of conceptual or toy models that clarified vital processes, features, or feedbacks within the Earth system, often relying on the principles of complexity science (Levin, 1999; Grinevald, 2007; Lenton et al., 2008; Scheffer, 2009).

During the mid-20th century, international scientific collaboration expanded, exemplified by the International Geophysical Year (IGY) 1957–1958 (Beynon, 2018). This unparalleled research endeavor coordinated the efforts of 67 countries to acquire a more comprehensive understanding of the geosphere, with a particular focus on glaciology, oceanography, and meteorology. Concurrently, rudimentary energy-balance models were developed to depict how the ice-albedo feedback could potentially propel the Earth into an alternative "snowball" stable state (Budyko, 1969; Sellers, 1969).

The rapid development of ecological and environmental sciences during the 1980s (Warde et al., 2018) led to the International Council for Science (ICSU) addressing international commitment and disciplinary integration in 1986 with the establishment of the International Geosphere Biosphere Programme (IGBP) (Dutreuil, 2016; Kwa, 2006; Uhrqvist, 2014). This program complemented the World Climate Research Programme (WCRP), initiated in 1980, which focused on the physical-climate component of the Earth system. The foundation for comprehending the biosphere's part in the Earth system's overall performance was established by these far-reaching international undertakings, such as the International Biological Program (IBP) and the International Biological Program of the Long Term Ecological Research (LTER) network (Kwa, 1987, 1993; Grinevald, 1996, 1998; Aronova et al., 2010). Simultaneously, the Daisyworld model developed in the 1980s demonstrated how feedback processes between life and its environment could result in global-scale temperature regulation (Watson and Lovelock, 1983).

Subsequently, more complex ESMs were developed, based on the fundamental physics and chemistry of the climate system and incorporating the exchange of energy and materials between the Earth's surface (land, ocean, ice, and increasingly the biosphere) and atmosphere (Dalmedico, 2010; Flato et al., 2013; He et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) evaluates potential future climate trajectories and their impacts, which are generated by models that take into account human greenhouse gas and aerosol emissions, to inform policy and governance. However, long-term GCM projections harbor significant uncertainties, stemming from parameterizations and the omission or inadequacy of constraints on feedback processes and interactions between the geosphere and biosphere (Kump and Pollard, 2008; Kiehl and Shields, 2013). Furthermore, GCMs lack the integration

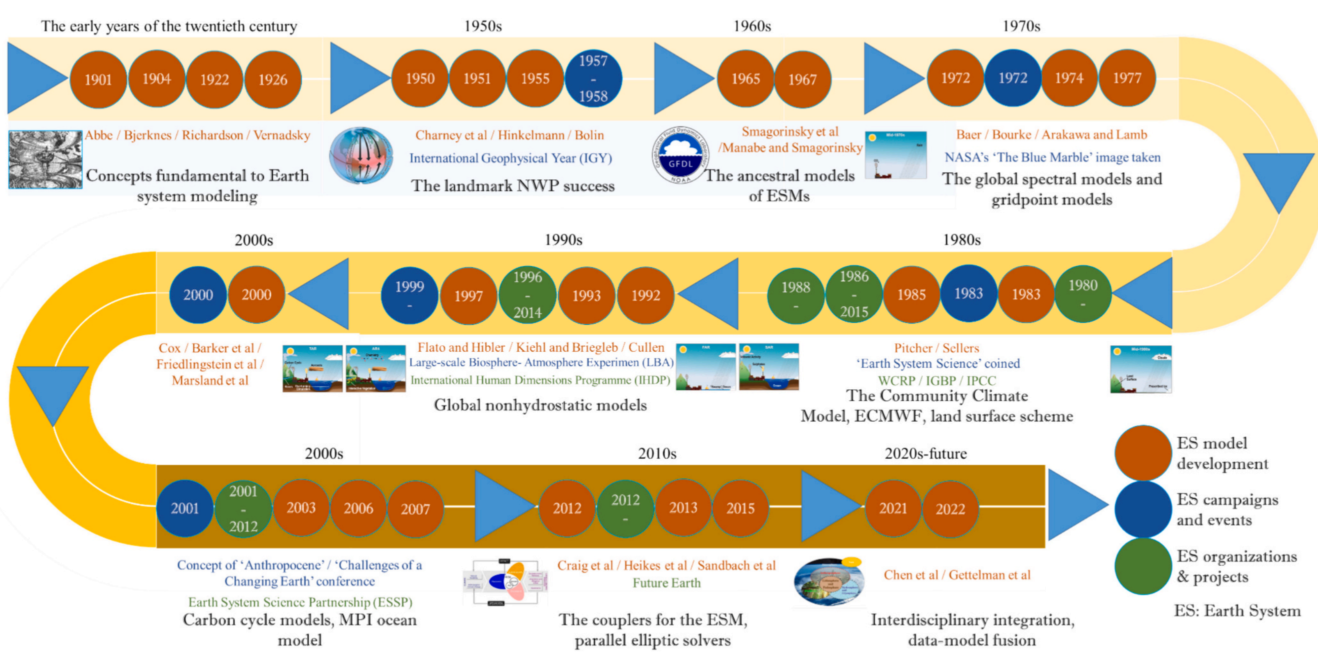

Fig. 1. One-hundred-year development of Earth system model.

of human dynamics as an intrinsic, interactive component of the model, treating them instead as an external force that disturbs the biogeophysical Earth system. Integrated assessment models (IAMs), on the other hand, encompass human dynamics by typically coupling economic models of varying complexity with less complex climate models (Van Vuuren et al., 2011; Shaman et al., 2013; Heymann and Dahan Dalmedico, 2019; Society et al., 2019).

The assortment of modeling tools accessible to the Earth system science (ESS) community is pivotal in advancing research efforts. While these tools are widely recognized for their ability to simulate potential future trajectories of the Earth system, their most significant value lies in their capacity to integrate knowledge. Models facilitate the assimilation of our rapidly expanding understanding of individual processes into a coherent framework, generate new concepts and hypotheses, and, most importantly, the model-observation integration serves as the ultimate assessment of our comprehension of the Earth system's functioning (Table 1).

3. Main challenges in ESMs

ESMs have been evolving for a century since "Weather Prediction by Numerical Processes" was mentioned in 1922 (Richardson, 1922). However, ESMs still face significant challenges, including the wide range of relevant scales (micro-to-global spatial scales, minutes-to-centuries temporal scales), nonlinear interactions of multi-scale processes (Fig. 2) and increasing human impacts, and the outsized impacts of extreme events on the environment.

Firstly, ESMs currently face challenges in fully capturing the bidirectional interactions between human activities and the Earth system. These models need to represent both how human actions modify the Earth system and how the resulting environmental changes affect human society.

Secondly, current ESMs lack the capability to incorporate dynamic processes within the Earth's crust and mantle and their interactions with other components of the Earth system, as well as the expression and recording of surface, lithospheric, and deep mantle dynamics in Earth's surface geology (mountain building, plate boundary deformation, and volcanism).

Thirdly, the cryosphere, comprising all terrestrial forms of snow and ice (snow cover, floating ice, glaciers, ice sheets, frozen ground, and permafrost), is a crucial component of the climate system due to its high reflectivity, insulation on land and ocean, and water storage in both short and long-term periods. However, many of these aspects are overly simplified in current ESMs. For instance, mountain glaciers and lake ice are typically not included in current ESMs.

In selecting the three major challenges for ESMs, we focused on those that we believe currently represent the most significant barriers to the accuracy and predictive power of these models. Nonetheless, it is crucial to acknowledge that there are additional key challenges within the domain of ESM advancement. For example, the inadequate representation of the biosphere within ESMs is an urgent issue (Bonan et al., 2024). Fortunately, the importance of biosphere-atmosphere coupling is acknowledged, and its advancements are forging ahead, causing such challenges to yield to those outlined above.

3.1. *Anthroposphere – new aspects of the human dimension in ESMs*

Human activities have progressively exerted a pervasive and enduring influence on Earth's environment, imprinting a lasting signature on our planet (Waters et al., 2016). Consequently, we find ourselves potentially residing within a novel geological epoch known as the Anthropocene. First proposed in 2000, the Anthropocene concept holds fundamental significance for two reasons. Firstly, Crutzen suggested the Anthropocene as a new epoch following the Holocene in the geological time scale (Crutzen, 2002). Secondly, within an Earth-system context, the Anthropocene represents a rapid departure from the 11,700-year, relatively stable climate-environmental conditions of the Holocene (Steffen and Pyke, 2004). Both points indicate that the Earth system has been persistently, widely, and unprecedentedly influenced by humans. Consequently, the anthroposphere, as a part of Earth's environment, has played as an increasing important factor in the Earth system (Motesharrei et al., 2016).

Humans' modification or construction of the anthroposphere (Kuhn and Heckelei, 2010) is not a physical area of Earth, yet it does cause considerable disruptions to the material and energy distribution in Earth's sub-systems within a brief period. This is associated with carbon, nitrogen, and phosphorus cycles, climate change, biodiversity loss, ecological turnover, environmental pollution, and other environmental issues, as well as social concerns such as high consumption, growing inequalities, and urbanization. Simultaneously, the Anthropocene concept provides a foundation for deeper integration of natural sciences, social sciences, and humanities, contributing to the development of sustainability science through research on the origins of the Anthropocene and its potential future trajectories (Lövbrand et al., 2009; Steffen et al., 2011). Therefore, human system models are an essential component of ESMs (Motesharrei et al., 2016), and it is not possible to properly predict the earth system without well estimating the changes of human dimension.

The Anthropocene, although still an informal term denoting humanity's pivotal role in reshaping the Earth's systems, has sparked fresh research and vigorous discussions within academia and the broader public sphere (Holmes et al., 2017; Prillaman, 2022; Waters et al., 2016). In recent years, the Anthropocene has sparked a surge of publications on human-environmental interactions worldwide, revealing many previously unknown processes of human impacts on environments at different spatial and/or temporal scales, potentially contributing to the evolution of Earth system dynamics (e.g. Huang et al., 2020, 2021; Zheng et al., 2021; Ren et al., 2022; Han et al., 2023; Chemke and Yuval, 2023).

Coupled human-environment systems necessitate the concurrent consideration of humans, the environment, and the nonlinearities between them, thus requiring the development and implementation of interdisciplinary collaborations (Galvani et al., 2016). Human-environment interaction (HEI) models can be employed to simulate human interactions with their surroundings (Renouard and Mokhtari, 2010). Henderson et al. (2016) developed a nonlinear mathematical model of human-environmental dynamics to study the coupled response of ecological and human behavior, emphasizing the crucial role that human activities play in this process. The Analysis, Integration, and Modeling of the Earth System (AIMES) project treated the Earth system as a multi-scale complex adaptive system, including various interactions on Earth, both between natural sub-systems and social sub-systems (Schimel et al., 2015). The AIMES project focused on considering and modeling human-environment interactions in the Anthropocene, regarding humans as internal components of the system rather than external participants.

Both the BNU-HESM (Yang et al., 2015) and DICE (Nordhaus, 1993) models connected human and Earth systems via temperature and emissions, transmitting data from the human component to the climate system. The resulting temperature change influenced gross domestic product (GDP) through a damage function. The GOLDMERGE (Bahn et al., 2006) model took a similar approach, but CO_2 concentration instead of emissions was passed from MERGE (Manne and Richels, 2005) to C-GOLDSTEIN (Edwards and Marsh, 2005; Calvin and Bond-Lamberty, 2018). The Copan: CORE World-Earth modeling framework enables the development of process-based models of global change and sustainable development in planetary social ecosystems, fostering a better understanding of the key mechanisms controlling coevolutionary dynamics between society and the natural environment (Donges et al., 2020). The C-ROADS climate model is linked to a social model of behavioral change to examine how interactions between perceived risk and emissions behavior influence projected climate

Table 1
Comparison of different ESMs.

Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
ACCESS-ESM1–5	UKMO UM atmospheric model (v7.3), same as ACCESS1.4, configured as N96 (1.875 × 1.25 degrees), resolution is 38 levels; CABLE land surface model with biogeochemistry (CASA-CNP) (CABLE2.4); 1 degree resolution GFDL MOM5 ocean model (code base is ACCESS-CM2); WOMBAT ocean carbon model; LANL CICE4.1 sea ice model (version ACCESS1.4).	Coupled Large-scale Aerosol Simulator for Studies in Climate (CLASSIC), HadGEM2-ES, CABLE2.4, GFDL MOM5.1, World Ocean Model of Biogeochemistry and Trophic-dynamics, CICE 4.1	OASIS3-MCT: MCT variant of OASIS coupler	The difference between Its CMIP5 parent (if applicable), minor atmospheric changes. The updated version of MOM and CICE, including land and ocean carbon cycle components to form an ESM.	Integration	(Ziehn et al., 2020) The Australian Earth System Model: ACCESS-ESM1.5. Journal of Southern Hemisphere Earth Systems Science 70, 193–214.doi:https://doi.org/10.1071/ES19035
AWI-CM-1-1-MR	The ECHAM6 climate model and FESOM1.4 sea ice-ocean model are coupled through the OASIS3-MCT coupler.		OASIS3-MCT coupler	In its low-resolution reference setting, AWI-CM actually simulates many aspects of the climate observed under constant conditions today (1990). More specifically, it was found that the performance of AWI-CM was at least the same as some of the most complex climate models participating in the fifth phase of the coupled model comparison project (Sidorenko et al., 2015). Regarding simulated climate variability, AWI-CM also performs well overall compared with those models (Rackow et al., 2016).	Integration	Sidorenko, D., Rackow, T., Jung, T., Semmler, T., Barbi, D., Danilov, S., Dethloff, K., Dorn, W., Fieg, K., Goessling, H. F., Handorf, D., Harig, S., Hiller, W., Juricke, S., Losch, M., Schröter, J., Sein, D. V., Wang, Q. 2015. Toward multiresolution global climate modeling with ECHAM6–FESOM. Part I: model formulation and mean climate. Climate Dynamics, 44(3–4), pp.757–780. Rackow, T., Goessling, H.F., Jung, T., Sidorenko, D., Semmler, T., Barbi, D. and Handorf, D., 2016. Toward multiresolution global climate modeling with ECHAM6-FESOM. Part II: climate variability. Climate Dynamics, pp.1–26.
BCC-CSM2-MR/HR	The model is coupled with an atmospheric model, atmospheric chemical aerosol model, land surface model, ocean model and sea ice model. Compared with the previous version, the main updates of model physics include the modification of deep convection parameterization, new scheme of cloud fraction, indirect influence of aerosol through clouds and precipitation, and gravity wave resistance caused by deep convection.	BCC-AGCM3-MR/HR, BCC-A VIM2.0, MOM4-L40	Flux coupler version 5	In terms of model physics. The main updates to the model physics include modifications to the parameterization of deep convection, new schemes for cloud composition, indirect influence of aerosols through clouds and precipitation, and gravity wave resistance caused by deep convection.	Integration	Wu, T., Lu, Y., Fang, Y., Xin, X., Li, L., Li, W., Jie, W., Zhang, J., Liu, Y., Zhang, L., Zhang, F., Zhang, Y., Wu, F., Li, J., Chu, M., Wang, Z., Shi, X., Liu, X., Wei, M., Huang, A., Zhang, Y., and Liu, X.: The Beijing Climate Center Climate System Model (BCC-CSM): the main progress from CMIP5 to CMIP6, Geosci. Model Dev., 12, 1573–1600, doi: https://doi.org/10.5194/gmd-12-1573-2019, 2019.
CAMS-CSM1–0	Contains atmospheric ECHAM5 module, terrestrial CoLM module, ocean MOM4 module, and sea ice SIS module.	ECHAM5_CAMS, CoLM 1.0, MOM4, SIS 1.0	GFDL coupler	(1) Modifying the conversion rate from cloud water to precipitation in the cumulus convection scheme can improve the simulation of cloud radiative forcing. (2) An effective solar zenith angle scheme, which takes into account the curvature of the atmosphere and its	Integration	Rong, (2019) CAMS CAMS_CSM1.0 model output prepared for CMIP6 CMIP. Version YYYYMMDD[1]. Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.1399

(continued on next page)

Table 1 (*continued*)

Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
CESM2	An open source, fully coupled model, consisting of ocean, atmosphere (low roof and high roof with integrated chemistry), land, sea ice, land ice, river, and wave modes. These modes exchange state and energy through couplers.	Community Atmospheric Model version 6 (CAM6), MOZART chemical mechanism, Community Land Model version 5 (CLM5), Community Ice Sheet Model version 2.1 (CISM2.1), Parallel Ocean Program (POP), BEC, CICE 5.1.2	CPL7/MCT	relation to the direct solar beam, and influence of the length of the light path parallel to the atmosphere. Compared with previous versions, CESM2 contains many substantive scientific and infrastructure improvements and functionality in all its components. These new advances include: atmospheric model components, major improvements in turbulence and convection representation, which open the way to analyze how these small-scale processes affect climate. Improved ability to simulate seasonal tropical variability patterns and influence global weather patterns. Greenland's land ice sheet model components can simulate the complex way the ice sheet moves and better simulate the ice bending toward the ocean. The global crop model component can simulate how cultivated land affects regional climate, including increasing the impact of irrigation, and how climate change affects crop productivity. Wave model components simulate how wind produces waves in the ocean, which is an important mechanism for upper ocean mixing. The updated river model component can simulate the surface water flow passing through the slope and entering tributaries before entering the main river channel. As well as a set of new infrastructure utilities, these utilities provide many new functions to simplify portability, case generation and user customization, test functions, and greatly improve robustness and flexibility.	Integration	Danabasoglu, G., Lamarque, J. -F., Bachmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kember, B., Kay, J. E., Kinnison, D., Kushner, P. J., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., Strand, W. G. The Community Earth System Model version 2 (CESM2). Journal of Advances in Modeling Earth Systems, 12 doi: https://doi.org/10.1029/2019MS001916
CNRM-CM6	CNRM-CM6–1 forms the physical basis of the CNRM Earth System Model, adding interactive aerosols, stratospheric chemistry, terrestrial carbon feedback, and marine biogeochemistry.	ARPEGE-Climat Version 6.3, NEMO: Nucleus for European Modeling of the Ocean version 3.6 (OPA)	OASIS-MCT coupler	Since the CNRM-CM5.1 version was used in CMIP5, all components have been upgraded. For oceans, sea ice, and rivers, there are no major changes in parameter	Integration	Voldoire et al., 2019. Evaluation of CMIP6 DECK experiments with CNRM-CM6–1, Journal of Advances in Modeling Earth Systems, doi:

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
				settings. In contrast, by using the latest parameter settings, the atmosphere and land surface composition have been completely re-examined. For atmospheric composition, the main changes include shallow and deep convection, microphysics, and the representation of turbulent processes. On land, the snow and soil schemes have been refined, while hydrology has been enriched to represent river floods and aquifers.		https://doi.org/10.1029/2019MS001683
CNRM-ESM2	CNRM-ESM2–1 is the second-generation CNRM Earth System Model developed by the CNRM/ CERFACS modeling team. It is derived from the physical power core of the ocean–atmosphere coupled climate model CNRM-CM6–1. CNRM-ESM2–1 explains a series of couplings between “Physical” and “Earth System (ES)” components.	TACTIC_v2, ARPEGE-Climat Version 6.3, REPROBUS-C (v2.0), SURFEX v8 modeling platform, NEMO: Nucleus for European Modeling of the Ocean version 3.6 (OPA), Pelagic Interaction Scheme for Carbon and Ecosystem Studies model volume 2 version trace gases (PISCESv2-gas)		By adding interactive ES components (such as carbon cycle, aerosol, and atmospheric chemicals), the model complexity of CNRM-ESM2–1 is higher than that of the atmosphere–ocean general cycle model CNRM-CM6–1. Because the two models share the same code, physical parameter settings, and grid resolution, they provide a fully traceable framework for the degree of influence on model performance in response to external forcing and future climate predictions. Through the use of various CMIP6 experiments, it has been proven that the ES model’s influence on the response of external forcing is more prominent than the performance of the current model.	Integration	Séférian R, Nabat P, Michou M, et al. Evaluation of CNRM Earth System Model, CNRM-ESM2–1: Role of Earth System Processes in Present-Day and Future Climate. Journal of Advances in Modeling Earth Systems, 2019, 11 (12): 4182–4227.
CanESM5	The physical model includes a predictive cloud microphysical scheme to control water vapor, cloud liquid water, and cloud ice; a statistical stratigraphic scheme; and an independent cloud-based mass flux scheme for deep convection and shallow convection.	CanAM5, NEMO, CMOC, CanOE	Canadian Coupler (CanCPL)	CanESM5 has updated CanESM2. The leap from version 2 to version 5 is substantial to make the internal model version consistent with the version released to the public. The update includes incremental improvements to the atmosphere, land surface, and terrestrial ecosystem models. The main change compared with CanESM2 is the implementation of new models and new couplers for the ocean, sea ice, and marine ecosystems. Model developers can continuously increase the limited computing	Integration	Swart et al., 2019. “The Canadian Earth System Model version 5 (CanESM5.0.3)”. Geoscientific Model Development vol. 12 (11), pp. 4823–4873. Swart et al., 2019. “CCCma CanESM5 model output prepared for CMIP6 CMIP 1pctCO2”. Earth System Grid Federation

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
				resources between model resolution, model complexity, and model throughput (i.e., the number of years of simulation).		
E3SM	Earth system scientific modeling, simulation, and prediction	EAM, ELM, MPAS, MPAS-O, MPAS-SI, MPAS-LI		E3SM Atmospheric Mode (EAM) is based on CAM5. Spectral element (SE) power core is selected as the default value, not an option, while cloud microphysics, shallow convection, and turbulence parameterization are replaced. Aerosol parameterization is greatly enhanced and vertical resolution more than doubled (30 to 72 levels). The physical parameterization has been tested and well adjusted for low-resolution and high-resolution applications, which is very important for solving the v1 water cycle problem.		Golaz, J.-C., P. M. Caldwell, L. P. Van Roekel and coauthors (2019). The DOE E3SM coupled model version 1: Overview and evaluation at standard resolution. Journal of Advances in Modeling Earth Systems, accepted, doi:https://doi.org/10.1029/2018MS001603
EC-EARTH3	The total circulation model of the atmosphere and ocean is described by Döscher et al., 2022. The atmosphere is a modified version of IFS cycle 36r4, including the land-surface program H-TESSEL. The ocean and sea ice model is NEMO-LIM3 version 3.6 with some modifications. The OASIS3-MCT coupler version 3.0 is used to exchange the fields between the atmosphere and ocean components.	Integrated Forecasting System (IFS), HUSESEL, NEMO 3.6 (Nucleus for European Modeling of the Ocean version 3.6), LIM3, LPJ-GUESS, TM5	OASIS3-MCT: MCT variant of OASIS coupler	The atmospheric composition of EC-Earth3 is based on the IFS cycle 36r4, not cycle 31r1. The descriptions of aerosols and aerosol–radiation interactions have been completely revised and includes aerosol–cloud interactions. Ocean and sea ice components have been upgraded from NEMO-LIM2 version 2 to NEMO-LIM3 3.6. The coupler has been upgraded from OASIS3 to OASIS3-MCT 3.0. The mandatory data has been changed from CMIP5 to CMIP6.	Integration	Massonnet et al., 2020 Replicability of the EC-Earth3 Earth system model under a change in computing environment. "Geoscientific model development", 12 March 2020, vol. 13, p. 1165–1178,https://doi.org/10.5194/gmd-13-1165-2020
ECMWF-IFS	The integrated earth system model developed by ECMWF in cooperation with the French Meteorological Agency constitutes the basis for data assimilation and forecasting activities. All the main applications required can be obtained through the computer software system of the Integrated Forecasting System (IFS).	HRES, ENS, NEMO (LIM-2), HRES-WAM, ENS-WAM		The climate surface deviation of ECMWF-IFS is relatively insensitive to the increase in atmospheric resolution, ranging from ~50 to ~25 km. However, increasing the horizontal resolution of the atmosphere while maintaining the same vertical resolution will increase the intensity of the cold shift in the lower stratosphere. In the coupled configuration, the sensitivity to increasing the resolution of the ocean model from 1° to 0.25° is high. However, this sensitivity to ocean	Integration	Roberts C D, Senan R, Molteni F, et al. Climate model configurations of the ECMWF Integrated Forecasting System (ECMWF-IFS cycle 43r1) for HighResMIP. Geoscientific model development, 2018, 11 (9): 3681–3712.

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
				resolution takes many years to fully manifest, and it is not so obvious in the first year of integration.		
FGOALS-f3	CAS FGOALS-f3-L consists of five parts: Finite Volume Atmosphere Model Version 2.2 (FAMIL); LASG/IAP Climate System Ocean Model Version 3; Community Land Model Version 4.0 (CLM4); Sea Ice Model (CICE4); and the version 7 of the coupler from the National Center for Atmospheric Research (NCAR).	FAMIL, SAMIL, LICOM3, CLM4, CICE4	CESM1.0 version 7 coupler (CPL7)	The physics module uses the scale perception scheme (RCP) that solves convective precipitation, in which convective precipitation and stratified precipitation are explicitly calculated with the same parameters.		He et al., 2019: CAS FGOALS-f3-L model datasets for CMIP6 historical Atmospheric Model Intercomparison Project simulation. Adv. Atmos. Sci., 36(8), 771–778, doi:https://doi.org/10.1007/s00376-019-9027-8.
FIO-ESM v2.0	FIO-ESM v2.0 is composed of five component models: General Atmospheric Circulation Model (AGCM), Land Surface Model, OGCM, Sea Surface Wave Model, and Sea Ice Model. The component models are coupled through a coupler. However, FIO-ESM v2.0 is different from FIO-ESM v1.0 in terms of coupling between the OGCM and Sea Surface Wave Model. In FIO-ESM v2.0, the Sea Surface Wave Model is directly coupled with the OGCM as a sub-routine in the OGCM, while in FIO-ESM v1.0, the Sea Surface Wave Model is connected to the coupler.	CAM5, CICE4, POP2, MASNUM, CLM4	CPL7	Compared with FIO-ESM v1.0, all component models of FIO-ESM v2.0 have been updated and their resolution has been optimized. FIO-ESM v2.0 performs CMIP6 diagnosis, evaluation and Klima characterization (DECK), and historical experiments. FIO-ESM v2.0 reproduces the climate change related to the global warming of SAT and SST and the reduction of AMOC very well.	R&D	Bao, Y., Song, Z., & Qiao, F. (2020). FIO-ESM version 2.0: Model description and evaluation. Journal of Geophysical Research: Oceans, 125, e2019JC016036. doi: https://doi.org/10.1029/2019JC016036
GFDL-ESM4.1	This unifies the progress of the past several phases of development work, highlighted by the integration of chemistry, carbon and ecosystems, including atmospheric dynamics, physics and chemistry, marine physics, biogeochemistry and ecosystems, sea ice and land physics, and biogeochemistry, with fully Interactive dust and iron cycling between land-atmosphere and ocean.	GFDL-AM4.1, GFDL-ATMCHEM4.1, GFDL-LM4.1, GFDL-OM4p5, GFDL-COBALTv2, GFDL-SIM4p5		CM4.0 and ESM4.0 combine the AM4 version of the new atmospheric model based on the FV3 power core. The main feature is the new convection parameterization. The ESM4 version has higher stratospheric resolution and more complete tropospheric and stratospheric chemistry material mechanisms. Both models include a version of the ocean model OM4. Based on the new MOM6 code, CM4 uses ¼-degree resolution, while ESM4 uses ½-degree resolution. ESM4 also integrates a more complete marine biogeochemical software package and the new Land Model LM4.1, as well as a unique dynamic vegetation module.	R&D	Dunne, J. P., L. W. Horowitz, A. J. Adcroft, P. Ginoux, I. M. Held, J. G. John, J. P. Krasting, S. Malyshev, V. Naik, F. Paulot, E. Shevliakova, C. A. Stock, N. Zadeh, V. Balaji, C. Blanton, K. A. Dunne, C. Dupuis, J. Durachta, R. Dussin, P. P. G. Gauthier, S. M. Griffies, H. Guo, R. W. Hallberg, M. Harrison, J. He, W. Hurlin, C. McHugh, R. Menzel, P. C. D. Milly, S. Nikonov, D. J. Paynter, J. Ploshay, A. Radhakrishnan, K. Rand, B. G. Reichl, T. Robinson, D. M. Schwarzkopf, L. A. Sentman, S. Underwood, H. Vahlenkamp, M. Winton, A. T. Wittenberg, B. Wyman, Y. Zeng, and M. Zhao (submitted). The GFDL Earth System Model version 4.1 (GFDL-ESM4.1): Model description and simulation characteristics. Journal of Advances in Modeling Earth Systems. 2019MS002008. Link to manuscript under review
GISS-E2	Provides the ability to simulate many different configurations of the Earth system model, including	SEA06, TCAD/TCADI, NINT, HYCOM		This model version is different from the previous model, mainly		Miller, R.L., G.A. Schmidt, L. Nazarenko, S.E. Bauer, M. Kelley, R.

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
	interactive atmospheric chemistry, aerosols, carbon cycle, and other tracers, as well as standard atmospheric, ocean, sea ice, and land surface components.			because the parameter settings of the atmospheric and ocean model components have been improved while the atmospheric resolution remains unchanged. For the modern climate, the model skills are significantly higher than the previous version. There have been specific improvements in the representation of change patterns, and significant improvements have been made in simulating the climate of the Southern Ocean (including sea ice).		Ruedy, G.L. Russell, A. Ackerman, I. Aleinov, M. Bauer, R. Bleck, V. Canuto, G. Cesana, Y. Cheng, T.L. Clune, B. Cook, C.A. Cruz, A.D. Del Genio, G.S. Elsaesser, G. Faluvegi, N. Y. Kiang, D. Kim, A.A. Lacis, A. Leboissetier, A. N. LeGrande, K.K. Lo, J. Marshall, E.E. Matthews, S. McDermid, K. Mezuman, L.T. Murray, V. Oinas, C. Orbe, C. Pérez García-Pando, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, D.T. Shindell, S. Sun, N. Tausnev, K. Tsigaridis, G. Tselioudis, E. Weng, J. Wu, and M.-S. Yao, 2021: CMIP6 historical simulations (1850–2014) with GISS-E2.1. J. Adv. Model. Earth Syst., 13, no. 1, e2019MS002034, doi: https://doi.org/10.1029/2019MS002034.
HadGEM3	The HadGEM3 series includes an atmosphere–ocean coupling configuration (with or without vertical extension in the atmosphere to include the stratosphere with good resolution) and an Earth system configuration (including dynamic vegetation, marine biology, and atmospheric chemistry).	NEMO	MCT variant of OASIS3-MCT-OASIS coupler	Since HadGEM2, the ocean and sea ice component models have been completely replaced by NEMO and CICE, respectively. The model has a new dynamic core, and important physics developments include the prediction of clouds, condensation, and rain, a two-step aerosol scheme, and improvements to the microphysics of liquid and mixed phase clouds. Since HadGEM2, major ground developments include multi-layer snowfall schemes and improved canopy–radiation interactions.	Integration	H. T. Hewitt et al., Design and implementation of the infrastructure of HadGEM3: The next-generation met office climate modeling system. Geosci. Model Dev.4, 223–253 (2011).
IITM-ESM	The Earth System Model (ESM) is an important tool that allows quantitative control of the physical, chemical, and biological mechanisms of the rate of change of the various elements of the Earth system (including the atmosphere, ocean, land, cryosphere, biosphere (land and ocean), and related components). ESM is essentially a coupled numerical model, which combines the processes within and between different Earth system components and is expressed as a set of mathematical equations. ESM enhances the basic understanding of the climate system, multi-scale variability, global and regional climate phenomena, and the	GFS, Noah LSM, GFDL-MOM4p1, Sea Ice Simulator (SIS)		In the latest version (IITM-ESM2.0), to obtain a global climate modeling framework for radiation balance, further improvements have been made, which are necessary to predict long-term climate change. IITM-ESM2.0 also shows simulation improvements in sea ice distribution, marine biogeochemistry, and average precipitation in the Asian monsoon region.		Krishnan R, Swapna P, Dey Choudhury A, et al. The IITM Earth System Model (IITM ESM). arXiv e-prints, 2021: arXiv: 2101.03410.

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
	prediction of future climate change.					
IPSL-CM6A	In addition to the physical atmosphere–land–ocean–sea ice model based on LMDz, ORCHIDEE, and NEMO (including LIM and PISCES sub-components) models, a representation of the carbon cycle is also included. The stratospheric chemistry and tropospheric chemistry modules that interact with aerosols can be activated. The past, present, and future changes in climate, and the influence of human factors on these changes can be studied.	LMDZ6A, ORCHIDEE surface model, NEMO: Nucleus for European Modeling of the Ocean version 3.2 (OPZ), NEMO: Nucleus for European Modeling of the Ocean (TOP/PISCES), Louvain La Neuve Sea Ice Model version 3	OASIS3-MCT: MCT variant of OASIS coupler	IPSL-CM6A-LR includes new versions of LMDz, NEMO, and ORCHIDEE. It improves energy and water conservation. The resolution of the atmosphere and land surface is increased from 96 × 95 × 39 to 144 × 142 × 79, and the resolution of the ocean increased from 2° to 1°. Compared with IPSL-CM5B-LR, the tuning stage of IPSL-CM6A-LR is longer and more thorough.	Integration	Boucher, O., J. Servonnat, A. L. Albright, O. Aumont, Y. Balkanski, V. Bastrikov, S. Bekki, R. Bonnet, S. Bony, L. Bopp, P. Braconnot, P. Brockmann, P. Cadule, A. Caubel, F. Cheruy, F. Codron, A. Cozic, D. Cugnet, F. D'Andrea, P. Davini, C. de Lavergne, S. Denvil, J. Deshayes, M. Devilliers, A. Ducharne, J.-L. Dufresne, E. DuPont, C. Ethé, L. Fairhead, L. Falletti, S. Flavoni, M.-A. Foujols, S. Gardoll, G. Gastineau, J. Ghattas, J.-Y. Grandpeix, B. Guenet, L. Guez, E. Guilyardi, M. Guimberteau, D. Hauglustaine, F. Hourdin, A. Idelkadi, S. Joussaume, M. Kageyama, A. Khadre-Traoré, M. Khodri, G. Krinner, N. Lebas, G. Levavasseur, C. Lévy, L. Li, F. Lott, T. Lurton, S. Luyssaert, G. Madec, J.-B. Madeleine, F. Maignan, M. Marchand, O. Marti, L. Mellul, Y. Meurdesoif, J. Mignot, I. Musat, C. Ottlé, P. Peylin, Y. Planton, J. Polcher, C. Rio, N. Rochetin, C. Rousset, P. Sepulchre, A. Sima, D. Swingedouw, R. Thieblemont, A. Traoré, M. Vancoppenolle, J. Vial, J. Vialard, N. Viovy, and N. Vuichard, Presentation and evaluation of the IPSL-CM6A-LR climate model, Journal of Advances in Modeling Earth System, 12, e2019MS002010, doi: https://doi.org/10.1029/2019MS002010, 2020.
MIROC-ES2	This model embeds terrestrial biogeochemical components with obvious carbon–nitrogen interactions to explain the control effect of soil nutrients on plant growth and terrestrial carbon sinks.	MIROC-AGCM, CHASER		The marine biogeochemical component of the model has been greatly updated to simulate the biogeochemical cycles of carbon, nitrogen, phosphorus, iron, and oxygen, so that the primary productivity of the ocean can be controlled through a variety of nutrient limitations. The model can reproduce the instantaneous global	Integration	Hajima T, Watanabe M, Yamamoto A, et al. Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. Geoscientific Model Development, 2020, 13 (5): 2197–2244.

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
MIROC6	MIROC6 consists of three sub-models: atmosphere, land, and sea ice–ocean. The atmospheric model is based on the CCSR-NIES atmospheric circulation model (AGCM; Numaguti et al., 1997), and the land surface model is based on the minimum depth of surface interaction and runoff processing (MATSIRO; Takata et al., 2003), including Oki and Sud (1998), a river path model based on the motion wave current equation (Ngo-Duc et al., 2007) and a lake module that considers one-dimensional thermal diffusion and mass conservation. The sea ice–ocean model is based on the CCSR ocean composition model (COCO; Hasumi, 2006). The coupled system calculates the heat and fresh water fluxes between the sub-models to ensure that all fluxes remain constant within the accuracy of the machine, and then exchanges the fluxes between the sub-models (Suzuki et al., 2009).	SPRINTARS, MIROC-AGCM, MATSIRO6, COCO4.9	Original coupler: the coupler system calculates the heat and fresh water fluxes between the sub-models to ensure that all fluxes are kept within the accuracy of the machine, and then exchanges the fluxes between the sub-models.	climate change and carbon cycle, as well as the observed large-scale spatial pattern of the terrestrial carbon cycle and upper-ocean biogeochemistry. This model demonstrates the historical disturbance of the nitrogen cycle by humans through land use and agriculture, and simulates the resulting impact on the terrestrial carbon cycle. The atmospheric model is based on the CCSR-NIES total atmospheric circulation model. The horizontal resolution is the T85 spectrum truncation. For latitude and longitude, the interval is a grid interval of approximately 1.4°. The vertical grid coordinates are mixed σ–p coordinates. The Spectral Radiation Transmission Model of Aerosol Species (SPRINTARS) is used as the aerosol module of MIROC6 to predict the mass mixing ratio of the main tropospheric aerosols. By combining the radiation plan and the cloud precipitation plan, SPRINTARS not only calculates the aerosol transmission process but also calculates the aerosol–radiation and aerosol–cloud interactions. The land surface model is based on the minimum advanced processing of surface interaction and runoff (MATSIRO). The model includes a river model based on the motion wave flow equation and a lake module that considers one-dimensional thermal diffusion and mass conservation. The horizontal resolution of the land surface model is the same as the horizontal resolution of the atmospheric composition. There are three layers of snow and six layers of soil at a depth of 14 m. The sea ice–ocean model is based on the CCSR ocean composition model (COCO). Using a three-pole horizontal	Integration	Tatebe H, Ogura T, Nitta T, Komuro Y, Ogochi K, Takemura T, Sudo K, Sekiguchi M, Abe M, Saito F, Chikira M, Watanabe S, Mori M, Hirota N, Kawatani Y, Mochizuki T, Yoshimura K, Takata K, O'ishi R, Yamazaki D, Suzuki T, Kurogi M, Kataoka T, Watanabe M, Kimoto M (2019) Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. Geosci Model Dev 12:2727–2765. doi: https://doi.org/10.5194/gmd-12-2727-2019

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
				coordinate system, the vertical grid spacing is 1°, and the meridian grid spacing ranges from 0.5° near the equator to 1° at mid-latitudes. There are 62 vertical levels in the mixed σ–z coordinate system. The coupler system calculates the heat and fresh water fluxes between the sub-models to ensure that all fluxes are kept within the accuracy of the machine, and then exchanges the fluxes between the sub-models.		
MPI-ESM/ HighResMIP	This is a comprehensive Earth system model, which consists of component models of ocean, atmosphere, and land surface. These components are coupled through the exchange of energy, momentum, water, and important trace gases (such as carbon dioxide).	HAM2.3, ECHAM6.3-HAM2.3, HAM2.3, JSBACH3.20, MPIOM1.6.3, HAMOCC6	OASIS3-MCT	The atmospheric composition ECHAM6.3 is directly coupled with the aerosol and cloud microphysics module HAM2.3 and ground model JSBACH3.20. The marine dynamics model MPIOM1.6.3 is directly coupled with the marine biogeochemical model HAMOCC6. These two main components are coupled through the coupler OASIS3-MCT.	Integration	Mauritsen T, Bader J, Becker T, Behrens J, Bittner M, Brokopf R et al. (2019) Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and its response to increasing CO_2. J Adv Model Earth Syst 11:998–1038. doi: https://doi.org/10.1029/2018MS001400 Gutjahr O, Putrasahan D, Lohmann K, Jungclaus JH, von Storch J-S, Brüggemann N, Haak H, Stössel A (2019) Max Planck Institute Earth System Model (MPI-ESM1.2) for the High-Resolution Model Intercomparison Project (HighResMIP). Geosci Model Dev 12:3241–3281. doi: https://doi.org/10.5194/gmd-12-3241-2019
MRI-ESM 2.0	This update includes various schemes and processes, including cloud schemes, turbulence schemes, cloud microphysical processes, interactions between clouds and convection schemes, resolution issues, cloud radiation processes, interactions with aerosol models, and numerical calculations. A new method for the parameterization of stratocumulus clouds and an improved cloud-ice fall plan are also included, which helps to increase low cloud cover over the Southern Ocean and reduce radiation bias.	MASINGAR mk-2r4c, MRI-AGCM3.5, MRI-CCM2.1, Land Surface (HAL), MRI. COM ver. 4.4	Simple Coupler (Scup)	The difference between this model and its CMIP5 parent (if applicable) is that the atmospheric vertical resolution has been increased from L48 to L80. Improved parameter settings related to clouds, aerosols, aerosol–radiation interaction, aerosol–cloud interaction, and gravity wave resistance. The ocean model has been updated to make the resolution of the meridian near the equator higher, and the parameterization of the sub-grid scale has been improved.	Integration	Kawai, H., Yukimoto, S., Koshiro, T., Oshima, N., Tanaka, T., Yoshimura, H., and Nagasawa, R.: Significant improvement of cloud representation in the global climate model MRI-ESM2, Geosci. Model Dev., 12, 2875–2897, doi: https://doi.org/10.5194/gmd-12-2875-2019, 2019.
NESM	NESMV3 upgraded the atmospheric and surface model components, and improved physical parameterization and coupled variable conservation.	ECHAM v6.3, JSBACH, Ocean PArallelise (OPA), CICE v4.1	OASIS3-MCT3.0	NESM v3 upgrades the atmospheric and ground model components, and improves the physical parameter setting and	Integration	Cao J, Wang B, Yang Y-M, Ma L, Li J, Sun B, Bao Y, He J, Zhou X, Wu L (2018) The NUIST Earth System Model (NESM)

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Model Name	Features	Module	Coupler	Advantage	Development model: R&D/ Integration	Introduction article
				coupling variable conservation.		version 3: description and preliminary evaluation. Geosci Model Dev 11:2975–2993. doi: https://doi.org/10.5194/gmd-11-2975-2018
NICAM16–9S	The model used in the study is named NICAM.16 gl09-L38 with NSW6, released in 2017, and includes the following components: Aerosol: prescribed MACv2-SP. Atmosphere: NICAM.16 (14 km icosahedral grid; 2,621,442 grid cells; 38 floors; highest level 40 km). Land: MATSIRO6 (excluding MOSAIC).	MACv2-SP, NICAM.16MATSIRO6		The updates of NICAM include the update of cloud microphysical solutions and terrestrial models, introduction of natural and man-made aerosols, and improvement of sub-grid-scale gravity wave resistance and coupling between clouds. In the NICAM16–9S simulation, it was found that the ice water content, high cloud cover, surface temperature in the Arctic region, location and intensity of the zonal average sub-tropical sub-current, and shortwave radiation in Africa and South Asia have been improved.	Integration	Kodama, Chihiro; Ohno, Tomoki; Seiki, Tatsuya; Yashiro, Hisashi; Noda, Akira T.; Nakano, Masuo; Yamada, Yohei; Roh, Woosub; Satoh, Masaki; Nitta, Tomoko; Goto, Daisuke; Miura, Hiroaki; Nasuno, Tomoe; Miyakawa, Tomoki; Chen, Ying-Wen; Sugi, Masato (2019). MIROC NICAM16–9S model output prepared for CMIP6 HighResMIP. Version YYYYMMDD [1].Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.1036
UKESM	The UKESM project is a collaborative project between NERC and the British Meteorological Service to develop, apply, and analyze the next generation of British ESMs. UKESM has two primary goals: develop and apply the world's leading ESM; and create a community of British ESM scientists.	NEMO, CICE, TRIFFID, JULES, UKCA, MEDUSA, and BISICLES	OASIS coupler	UKESM uses the NEMO ocean model and CICE sea ice model, as well as the JULES land surface model with TRIFFID dynamic vegetation. In addition, UKESM uses UKCA to simulate atmospheric chemistry and aerosols, and MEDUSA to simulate marine biogeochemistry. The BISICLES model provides dynamic ice sheets. The interface between each sub-model uses the OASIS coupler.	Integration	Sellar A, Jones C, Mulcahy J, Tang Y, Yool A, Wiltshire A, O'Connor F, Stringer M, Hill R, Palmieri J, Woodward S, Mora L, Kuhlbrodt T, Rumbold S, Kelley D, Ellis R, Johnson C, Walton J, Abraham N, Andrews M, Andrews T, Archibald A, Berthou S, Burke E, Blockley E, Carslaw K, Dalvi M, Edwards J, Folberth G, Gedney N, Griffiths P, Harper A, Hendry M, Hewitt A, Johnson B, Jones A, Jones C, Keeble J, Liddicoat S, Morgenstern O, Parker R, Predoi V, Robertson E, Siahaan A, Smith R, Swaminathan R, Woodhouse M, Zeng G, Zerroukat M (2019) UKESM1: description and evaluation of the UK Earth system model. J Adv Model Earth Syst. doi:https://doi.org/10.1029/2019MS001739

change (Beckage et al., 2018).

As prototypes for the integrated assessment of climate change and economic dynamics, two agent-based models offer a promising approach to analyze coupled climate, energy, and macroeconomic dynamics (Lamperti et al., 2019). These models enable the bottom-up reflection of climate damage and its cross-sectoral penetration while naturally embedding distribution issues and explaining the role of finance in maintaining economic development and shaping the dynamics of energy transformation. An integrated socio-energy-ecologic-climate model framework for understanding the role of human-natural system interactions in climate change has been presented (Ramanathan et al., 2022), wherein climate stabilization imposed by feedbacks between global warming and societal actions was constrained to decarbonize energy use and scale up atmospheric carbon extraction. The energy-climate feedbacks are modeled through four warming-dependent response times for societal, policy, and technological actions inferred from historical data.

Nevertheless, several issues and uncertainties persist within these

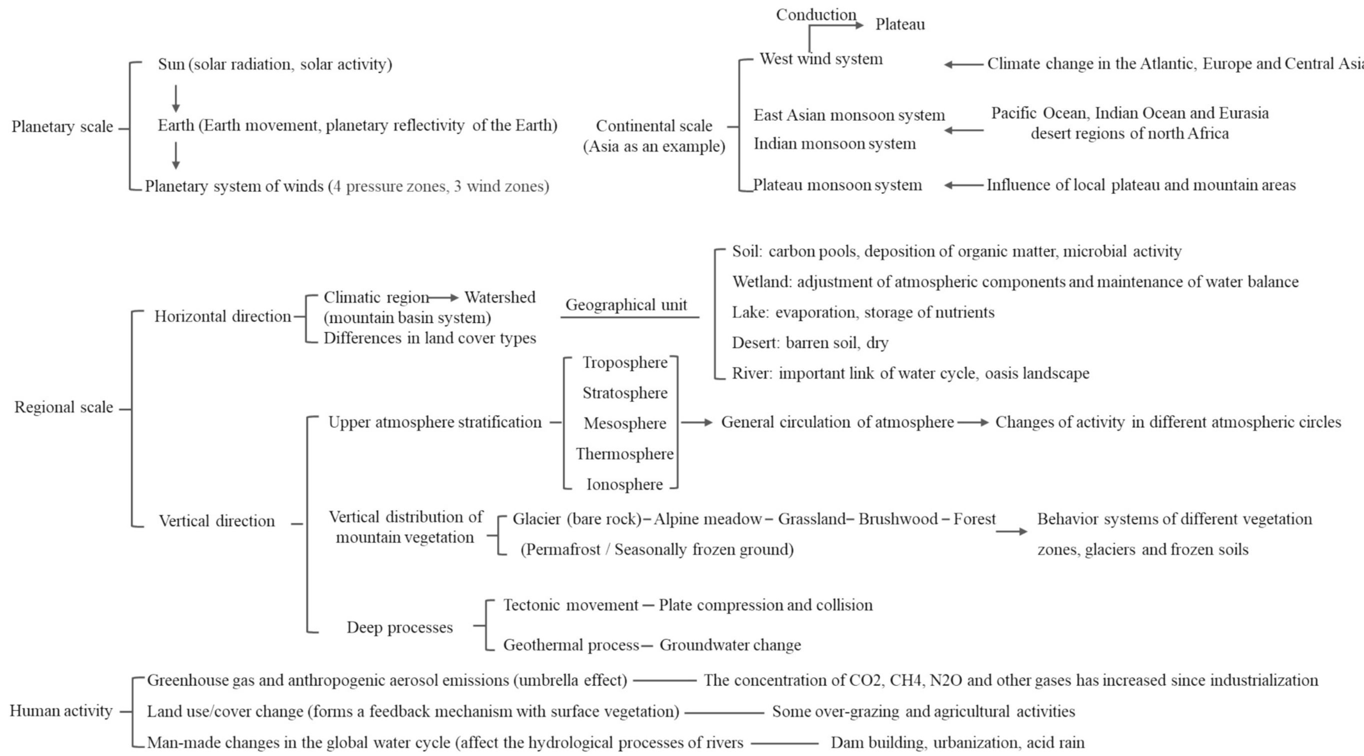

Fig. 2. The processes of spheres in ESMs at different scales.

coupled models. For instance, human activities in BNU-HESM1.0, such as governmental policies, employment, and other processes, contain numerous uncertainties. These intricate processes are heavily parameterized and sometimes disregarded in DICE (Yang et al., 2015). According to the 2016 DICE model, non-CO_2 forcings are introduced as an 'exogenous forcing' term, superimposed on radiative forcing from CO_2 (Nordhaus, 2017). Furthermore, the DICE climate model utilized in the coupled climate-social model to estimate warming exhibits a sluggish temperature response and inadequate representation of carbon-cycle feedback (Dietz et al., 2021).

The coupling of human-environment interactions is an increasingly significant driving factor in Earth system dynamics, with modeling capabilities playing a crucial role in research domains such as vulnerability analysis. However, a limited number of relevant theories and models exist (Turner et al., 2003; Schimel et al., 2015). Investigating human-environment interactions necessitates interdisciplinary and multidisciplinary collaboration, as well as the concerted efforts of individuals and teams capable of integrating across various disciplines. Achieving interdisciplinarity is a complex process that demands a systemic perspective and an understanding of the intricacies of human-environment interactions, rather than attempting to oversimplify the process (Moran and Lopez, 2016).

Historically, research on human and Earth systems has been conducted separately, with distinct teams and models dedicated to each area. Although these communities and models are increasingly interconnected and feedbacks have the potential to impact both human and Earth systems, substantial uncertainty exists in these results, and truly integrated studies remain scarce. To accurately quantify the sign and magnitude of human-Earth system feedbacks, more research, models, and studies are necessary (Calvin and Bond-Lamberty, 2018). While some Integrated Assessment Models (IAMs) incorporate climate models with human systems, they primarily focus on economic aspects, such as climate change impact costs, and do not facilitate two-way feedbacks. Climate models generally lack dynamic representations of human emission behaviors that evolve in response to perceived climate change risks, and emission behaviors are not static but likely to respond to extreme weather event changes. Social processes, which have been predominantly absent from climate models and IAMs, are pivotal and dynamic constituents of the Earth system. Two-way linkages between human behavior and climate could significantly affect greenhouse gas (GHG) emissions and temperature change in a manner unattainable through uncoupled models. The perception of risk from extreme events related to climate change can influence emission behaviors to minimize GHGs (Beckage et al., 2018). Despite various attempts to connect the economy (or its components) to climate evolution, the outcomes have frequently been unsatisfactory and critiqued.

Although agent-based models hold considerable promise, substantial progress is required for them to match the richness of many existing IAMs and address their primary issues. Research in this area should encourage this approach (Lamperti et al., 2019). Socio-political-technical processes that determine climate policy and emission trajectories are often treated as exogenous factors in the majority of climate change models (Beckage et al., 2020; Peng et al., 2021). The lack of quantitative analysis of human-natural system interactions' role in addressing climate change hinders the redesign of energy and economic systems for climate stabilization (Ramanathan et al., 2022).

3.2. Lithosphere – the long-term evolution of the Earth system

The lithosphere, constituting the Earth's rigid outer layer, has typically been regarded as a consistently stable component in most ESMs. Comprising the brittle crust and the upper mantle's top section, the lithosphere is delimited by the atmosphere above and the asthenosphere (another part of the upper mantle) below. It supports the Earth's surface, regulates the planet's temperature, and influences the movement of water and other elements, and provides proxy indicators to reconstruct paleoclimate temperature (Kaufman and Broadman, 2023) and to help understand carbon cycle-climate feedbacks relevant to the Anthropocene (Tierney et al., 2020). Furthermore, the lithosphere's interactions with other Earth systems are complex and dynamic. For example, rock moisture storage of considerable magnitude is probably widespread, yet it is not accounted for in the hydrological and land-surface models that are employed to support forecasting regional and global climatic patterns (Rempe and Dietrich, 2018). Meanwhile, glacial movements can grind lithospheric rocks into powder, while weathering and erosion by wind and rain contribute to soil formation. The terrestrial lysocline, akin to the movement of the oceanic lysocline in response to acidification, is expected to shift due to anthropogenic CO2 emission (Goddéris and Brantley, 2013). These kind perturbation responses should be considered in ESMs to make reasonable assessment of human activities between lithosphere and other Earth systems (Milkoreit, 2023; Otto et al., 2020).

Over geological timescales, tectonic plate shifts and redistributions have altered oceanic and atmospheric circulation patterns, precipitation, vegetation, geomorphological features, river flow, and even Earth's life evolution. The uplift of high mountains and formation of valleys and plains have reshaped ecosystems, interacting with all life forms and documenting Earth's surface processes. Despite advancements in scientific knowledge regarding Earth's surface interactions and the increasing availability of novel monitoring technologies, the processes that create and degrade landscapes remain largely unknown (Council, 2010).

At shorter timescales, volcanic eruptions and powerful earthquakes fundamentally impact Earth environments, inducing regional hydrological changes, atmospheric aerosol alterations, and dynamic chemical weathering, which consequently affect various interconnected systems (Knight et al., 2021; Morra et al., 2021; Holt, 2022; Van Zelst et al., 2022).

Time serves as a crucial organizational principle in Earth science, particularly in tectonics, as understanding geodynamic processes and the atmosphere-biosphere interaction hinge upon the quality of constraints on these processes' timing and speed (Huntington et al., 2017). Exploring the early Earth's behavior before plate tectonics and when accretion and planetary differentiation were the main influences, will help to comprehend the emergence of plate tectonics on rocky planets. Additionally, it will help elucidate the atmosphere, cryosphere, and hydrosphere's origins, as well as the emergence and maintenance of habitable worlds (Charco et al., 2020).

Recent advancements in techniques, such as K/Ar dating of fault gouge clays (Haines and van der Pluijm, 2008), U/Pb dating of calcite in mineralized fault zones (Roberts and Walker, 2016), and advanced microanalytical technique (Mottram et al., 2015) now enable direct dating of brittle deformation features. Enhancements to both existing and new geochronometers serve as a model for the tectonics community to make considerable progress in comprehending processes from minute to global, and from geological to human eras.

Since the 1970s, many global plate tectonic models have been proposed to reconstruct Earth's evolution through deep time (Verard, 2019). These reconstructions have proven invaluable for the scientific community. Past Earth reconstructions are utilized, at least as general frameworks, in a large majority of geoscience studies. For instance, understanding mantle dynamics requires a plate tectonic model as the surface condition, while a correct plate tectonic model provides the necessary framework to study paleogeography. Transitioning from a plate tectonic model to a paleogeographic model is a delicate process. While a plate tectonic model positions landmasses and defines geodynamic environments over time, paleogeographies are primarily determined by the association of topography and sea level, with climate (i.e., ocean-atmosphere-cryosphere), hydrography, and biosphere further defining paleoenvironments. To model such cycles, coupling an ad hoc full plate tectonic model with a global climate model is required to quantify various material fluxes, followed by modeling the biochemical cycles concerning those fluxes.

Choosing a reconstruction model has implications for understanding external geodynamics. The next frontier involves coupling plate tectonic models with other models (see Vérard, in press), which can, in turn, illuminate the validity of choices and assumptions made in reconstructing the past.

Extensive geological and thermal chronology toolkits, developed in the past 15 years and/or augmented by microanalysis techniques and chemical mapping of mineral heterogeneity, can be used to link surface and deep Earth processes from outcrop to plate scales (Huntington and Klepeis, 2018). At the regional scale, combining thermal chronology data from multiple chronometers with time-related thermal and kinematic models has transformed our ability to reconstruct mountain wedge structures in four dimensions (McQuarrie and Ehlers, 2015; Fox et al., 2015).

The coupling of plate tectonic models with other global models necessitates specific architecture. Not only must plate tectonic models consider feedback from other models, but they must also be designed such that each feature tracks its past evolution. Mantle convection models require plate tectonic models as boundary layers on the surface. In return, convection models provide independent datasets that can confirm or refute some reconstructions, especially when comparing convection model results with seismic tomography (Gillooly et al., 2019). Paleo-stress models, operating at the scale of tectonic plates, can also serve as data sources to support or refute geodynamic scenarios, constraining plate boundary geometry, particularly in terms of defining synthetic mid-ocean ridges (as done, in particular, by Gerya, 2013). Moreover, erosion-sedimentation and paleoclimate are heavily dependent on vegetation. Consequently, plate tectonic models will require coupling with continental vegetation models, such as BIOME4 (Kaplan et al., 2003), or marine models, such as Darwin (Follows and Dutkiewicz, 2011; http://darwinproject.mit.edu). Other global models must be coupled or, at a minimum, used as input or output data for validation. This applies specifically to climate-related geochemical models, such as GeoCarb (Berner, 1998, 2006) or GeoClim (Donnadieu et al., 2006, 2009), geochemical models related to magmatism, and astronomical models, such as La2010 (Laskar et al., 2011; Shaviv and Veizer, 2003). The new generation of global plate tectonic models can only be achieved by combining numerous teams working on a variety of topics. The coming decade will undoubtedly witness a remarkable leap in this research field.

Understanding deformation and the processes linking Earth systems, from geologic to human timescales, represents a significant challenge. Integrating observational data obtained from natural rocks, experimental outcomes, and computational modeling surpasses fundamental kinematics and static descriptions of Earth's deformation and surface processes, facilitating the examination of dynamic and transient phenomena. This advancement ushers in a new era of cross-disciplinary research, enabling the investigation of dynamic interactions among all Earth's domains, including the core, mantle, asthenosphere, lithosphere, hydrosphere, atmosphere, and biosphere.

3.3. Cryosphere – a crucial role in global environmental shifts

The cryosphere constitutes the Earth's solid surface component, playing a crucial role in global environmental shifts, such as regulating surface heat energy and sea levels, and modulating regional to global climatic patterns. The cryosphere, with its sea ice, lake ice, river ice, snow, glaciers, ice sheets, permafrost, and seasonally frozen soil, is a key factor in the global climate. Its influence is felt through water flux, cloud formation, precipitation, hydrological processes, atmospheric conditions, and oceanic circulation (Steffen et al., 2018). Furthermore, the cryosphere, displaying a heightened sensitivity to climate change, has been affected by global warming, resulting in the melting of glaciers, ice sheets, and permafrost, thus leading to a rise in sea levels (Su et al., 2019). Consequently, enhancing our understanding of the cryosphere's role is essential in reducing uncertainties in cold-region climate change predictions (Giorgetta et al., 2013).

The cryosphere maintains intricate interactions with other Earth spheres. In the context of global warming, the cryosphere has undergone significant alterations, thus amplifying its impacts. The cryosphere's influence on the atmosphere manifests in various ways. Primarily, the melting of glaciers and snow alters surface albedo, subsequently impacting the energy balance. Secondly, the thawing of permafrost leads to the decomposition of organic carbon by microorganisms, releasing it into the atmosphere and exacerbating global warming, as permafrost stores substantial amounts of organic carbon. Additionally, the melting of glaciers, snow, ice sheets, and other cryospheric components results in increased water influx into oceans, thereby affecting the global hydrological cycle and sea levels.

The cryosphere's influence on the lithosphere primarily manifests in two ways. Firstly, glaciers and snow contribute to lithospheric erosion and morphological alterations. Secondly, expansive glaciers and ice sheets shield the lithosphere from other weathering processes. In terms of the biosphere, the cryosphere's impact mainly pertains to ecosystem dynamics. Land ice fluctuations modify soil water and thermal conditions, subsequently influencing terrestrial ecosystems. Additionally, the cryosphere's melting leads to a substantial influx of freshwater into oceans, profoundly impacting marine ecosystems. The anthroposphere's relation to the cryosphere can be divided into two aspects. On one hand, glacial and snowmelt generate vast freshwater resources, benefiting human production and life. Conversely, the extensive cryosphere melting raises sea levels, posing challenges to coastal human populations (Su et al., 2019).

In summary, the cryosphere maintains strong connections with other spheres, engaging in reciprocal interactions. Consequently, incorporating the cryosphere into ESMs (ESMs) and considering the couplings between the cryosphere and ESMs holistically bear far-reaching implications. However, current cryosphere representations in ESMs often only involve singular or limited cryospheric components (typically those with smaller inertial properties) and changing rates of these components are not comprehensively considered.

Snow constitutes a critical element in the cryospheric climate system due to its perennial coverage over large continental ice sheets, Earth's sea ice, and significant proportions of the Northern Hemisphere's seasonally ice-free land areas. The unique physical properties of snow allow it to play various roles within the Earth system due to its fundamental influence on the water balance, thermal regimes, vegetation, and carbon flux (Qu and Hall, 2014; Bennett et al., 2021). A project named ESM-SnowMIP, an internationally coordinated modeling initiative, aims at evaluating existing snow schemes, encompassing those incorporated in Earth system models, across a diverse range of environments (Krinner et al., 2018). The incorporation of the thermodynamic effects of snowmelt in the open ocean is a key factor contributing to the cooling propensity of the Canadian Earth System Model version 5 (CanESM5) (Swart et al., 2019). A multilayer snow scheme was introduced in the ECMWF-IFS in order to yield a more responsive surface temperature, especially for deep snowpacks (Arduini et al., 2019) and representation of snow density in the Community Earth System Model Version 2 (CESM2) can make improvements in the wintertime surface temperature variability (Simpson et al., 2022). The Goddard Snow Impurity Module (GOSWIM) - a module created to assess the deposition of dust, black carbon (BC), and organic carbon (OC) on snow impurities and albedo - has been integrated with the NASA Goddard Earth Observing System Version 5 (GEOS-5) Earth System Model (Yasunari et al., 2016). The interaction between shortwave (SW) radiation, snow, and vegetation was developed in the first version of the U.K. Earth System Model UKESM1 to reduce a substantial SW radiation bias (Sellar et al., 2019).

Ice sheets, as a crucial component of the cryosphere, comprise large expanses of continuous glacier ice enveloping land, also referred to as continental glaciers. Accounting for over 99 % of Earth's freshwater, ice sheets' release into oceans significantly impacts global climate (Kapsch et al., 2017). Ice sheets' response to forced alterations, such as anthropogenic climate forcing, is influenced by their interactions with other parts of the Earth system. These interactions encompass the response of ice sheets to Earth system forcing, the Earth's response to ice sheet alterations, and the coupled response of ice sheets and Earth systems (Fyke et al., 2018). Investigating these interactions necessitates coupling Ice Sheet Models (ISMs) and ESMs. Employing ESMs in conjunction with ISMs to tackle interactions and feedbacks between ice sheets and other components of the Earth system is still a complicated undertaking. Firstly, the Surface Mass Balance (SMB) must be downscaled from the low-resolution atmospheric grid of current ESMs to high-resolution ice sheet topography (Kapsch et al., 2017; Sellevold et al., 2019; Van Kampenhout et al., 2019). Secondly, current ESMs often employ ice sheets as static components, despite their continuous evolution and lack of fixed boundaries (Fyke et al., 2018). Ice sheet processes are frequently oversimplified in current ESMs, as ice sheet changes were traditionally considered to occur over extended timescales compared to oceanic and atmospheric alterations. However, numerous observations indicate an escalating rate of mass loss from the Greenland ice sheet, necessitating comprehensive process-based models to investigate its role in climate change. The EC-Earth-PISM climate-ice sheet model system was thus created, incorporating the EC-Earth (version 2.3) global climate model and the Parallel Ice Sheet Model (PISM, version 0.5), which incorporates a dynamic Greenland Ice Sheet into the EC-Earth global climate model (Madsen et al., 2022).

Permafrost constitutes another significant cryospheric component. With global warming, the vast amount of organic carbon stored in permafrost becomes susceptible to microbial decomposition. To effectively assess this potential carbon–climate feedback, permafrost models must be integrated into ESMs. The coupling effect of ESMs and permafrost models should be elucidated, simulating the physical processes of permafrost and determining its melting rate (Chadburn et al., 2015). Permafrost, or permanently frozen soil, currently stores approximately one-quarter of global soil carbon. A warming climate renders this carbon increasingly vulnerable to decomposition and eventual release into the atmosphere as greenhouse gases. However, the uncertain fate of permafrost carbon under warming, with varying model estimates, underscores the need for better modeling of soil moisture changes due to thaw, as soil drying significantly alters CO2 and CH4 emissions, impacting the projected global warming potential (Lawrence et al., 2015). Estimating the resulting climate feedback using ESMs presents challenges due to their high complexity and computational cost, complicating efforts to estimate uncertainty, explore novel scenarios, and couple them with alternative models.

Several General Circulation Models incorporate essential permafrost processes, such as the Max Planck Institute for Meteorology Earth System Model (MPI-ESM). This model was developed to estimate the uncertainty in simulated climate resulting from parameterization uncertainties in permafrost hydrology (de Vrese et al., 2022). The Hector model includes permafrost as a separate soil carbon pool that remains inert until thawing (Woodard et al., 2021). Proposed improvements for permafrost process modeling encompass the following aspects: (1) the heat capacity and thermal conductivity of frozen soil, (2) the organic layer near the surface in high-latitude Taiga and tundra regions, and (3) unfrozen water in areas with subzero ground temperatures (Yokohata et al., 2020). The GCM depictions of permafrost processes, due to the lack of observational data, are often quite basic, as evidenced byAlexeev et al. (2007), Nicolsky et al. (2007), Lawrence et al. (2008), Rinke et al. (2008), Koven et al. (2009) and Gouttevin et al. (2012).

Overall, the accurate quantification of teleconnection impacts remains limited due to inadequate observations, particularly concerning the ocean and cryosphere. For instance, it is unclear how teleconnections and corresponding atmosphere-ocean interactions affect oceanic heat content (Gille, 2008; Cazenave and Llovel, 2010; Stammer et al., 2013; Schmidtko et al., 2014; Spence et al., 2014); how anthropogenic changes in the mean Antarctic state alter teleconnection signal impacts (Fyfe et al., 1999; Lu et al., 2007; Wang et al., 2014); whether tropical-polar teleconnections will influence Antarctic tipping points (Lenton et al., 2008; Steffen et al., 2015); broader implications for ecosystems (Kennicutt et al., 2015; Kennicutt et al., 2019); and the relative significance of different ocean basins (Li et al., 2016; Simpkins et al., 2016). Addressing these questions necessitates a deeper comprehension of teleconnection processes and dynamics and heavily relies on continuous observations and the ongoing development of ESMs (Li et al., 2021).

4. Opportunities in the future development of ESMs

4.1. Anthroposphere – incorporating human-nature interactions in ESMs

ESMs must take into account the complex interactions between human activities and natural systems, and how they affect each other over time (Fig. 3). Human activities exert a profound influence on the Earth system through a variety of complex and interconnected pathways. These pathways are often multifaceted, involving physical, chemical, biological, and socio-economic processes that span local to global scales (Steffen et al., 2015). Studies using coupled Earth–human systems that have been published to date is limited. More studies on such a coupling are needed to robustly assess the sign and magnitude of human–Earth system feedback. Furthermore, these systems need to include a 'diversity of approaches' (Verburg et al., 2016) and a 'cross-comparison of models' (Zvoleff and An, 2014). However, the specific approach should use 'appropriate computational and conceptual frameworks' (Palmer and Smith, 2014) to ensure that appropriate type of model (the racehorse) be applied for answering the target research question (the race course)' (Van Vuuren et al., 2011). Verburg et al. (2016) suggest that 'plug-and-play component programming' could help to address these limitations, enabling the development of tailored modeling systems and model intercomparisons. Regardless of the approach to integrating components, any coupled model should track the propagation and accumulation of errors (Verburg et al., 2016).

There are several tools that incorporate human activities and policies into ESMs, such as IAMs which were employed to assess the costs and benefits of various policies to address climate change (UK government, 2006). Agent-based models (ABMs) were also employed to model complex systems in social science, thereby exploring the relevant social mechanisms in empirical situations (e.g.). These are just a few of the tools that incorporate human activities and policies into ESMs. An examination of the impact of goods and services on the environment through input-output analysis is conducted on markets, urban cities, and organizations. It can be used to assess the environmental impact of different economic policies, such as changes in trade or investment. Social network analysis examines the social relationships between individuals or groups and how they influence decision-making. It can be used to study how social networks affect the adoption of new technologies or behaviors that impact the environment. By incorporating these tools into ESMs, researchers can better understand how human activities and policies affect the environment and make more informed decisions about how to address global environmental challenges. Among which, ABMs simulate the behavior of individual agents, such as households or firms, and how they interact with each other and the environment. ABMs, which simulate the behavior of individual agents such as households or firms and how they interact with each other and the environment, can be employed to investigate how alterations in policies or technological advances influence the behavior of different agents and their effect on the environment. Demonstrated to be a potent instrument for modeling and comprehending human decisions (An, 2012; An et al., 2014). ABMs can be used to simulate a wide range of systems, from social and economic systems to ecological and biological systems. ABMs typically involve defining a set of rules for the behavior of agents and simulating the behavior of these agents over time. The behavior of agents can be influenced by their environment, and this environment can be updated based on the behavior of agents. ABMs are capable of addressing a diverse array of questions, including how modifications in individual behaviors influence the collective system behavior, and how varying types of interactions among agents shape the system's dynamics. However, ABMs' ability to capture real-world complexity and predict system behavior is limited by its reliance on simplifications, assumptions, and data-driven methods, while managing complex systems and interpreting results requires careful consideration of these factors (Abar et al., 2017).

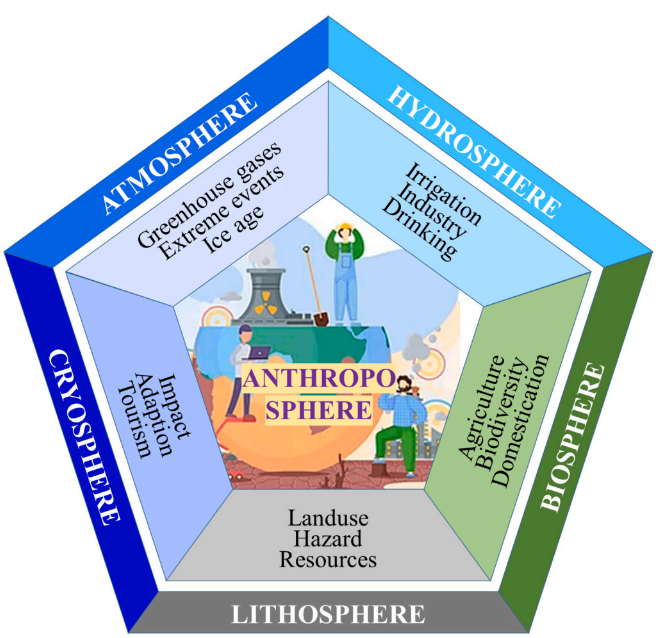

Fig. 3. The interactions between anthroposphere and other spheres.

Moreover, there is a growing demand for interdisciplinary research (Palmer and Smith, 2014) and enhanced communication within interdisciplinary teams (Newell, 2012; Hibbard et al., 2010). Fostering community development can facilitate this communication and interaction (Laniak et al., 2013; Mauser et al., 2013). Laniak et al. (2013) also emphasized the importance of openness, asserting that transparency and collaboration could promote accessibility and innovation. Additionally, there is a need for improved data and comprehensive metadata (Verburg et al., 2016; Palmer and Smith, 2014). In summary, more studies are necessary to advance the understanding of human–Earth system feedbacks and to reliably quantify the sign and magnitude of these interactions.

4.2. Lithosphere – including its evolution in ESMs

Currently, plate tectonic movement is predominantly attributed to thermal convection in the mantle; however, a detailed quantitative model to describe these processes remains elusive. Kaban et al. (2016) developed a new generation of global crustal and mantle dynamics models based on an extensive analysis of gravity, GPS, and other geophysical data. This novel model integrates the primary physical parameters, which were consistently validated using a unified dataset and modeling technology. The model's relevant parameters included the locations of major lithospheric boundaries and the physical properties of principal layers (encompassing seismic velocity, density, and temperature). Utilizing these results, the gravitational field component induced by heat and compositional changes in the upper mantle was determined. After eliminating the influence of isostatic compensation lithosphere from the observed geoid, the residual field primarily reflects the impact of the deep mantle structure and dynamics. The residual geoid was then employed as the primary constraint for global dynamic modeling.

Building on this foundation, further development of new-generation global crustal and mantle dynamics models is underway, focusing on comprehensive analyses of gravity, GPS, and other geophysical data. Emphasis is placed on the development of comprehensive lithospheric models (including rheological models) and simulations of lateral viscosity changes in the mantle on the global geoid and surface plate velocity. Hager and O'Connell (1981) proposed a conceptually simple model based on the boundary layer formula of the convection problem to approximate plate motion and mantle convection. This plate motion process is directly solved in a three-dimensional manner, elucidating the coupling relationship between the plate and mantle convection system. Plate motion models should be coupled with other models to accurately determine paleo-height. Investigating the material properties, chemistry, mineral physics, and dynamics of the solid Earth is a captivating endeavor, essential for addressing 21st-century challenges related to energy, water, and natural disaster resilience. Efforts to comprehend the solid Earth confront obstacles, as the Earth's interior remains largely unobservable and is expected to continue being so in the future (Bergen et al., 2019).

4.3. Cryosphere – an important yet overlooked component of the Earth System

Promising advancements are underway, such as the European Integrating Project for research and development in ESMs called "Comprehensive Modeling of the Earth System for Better Climate Prediction and Projection." This project aims to incorporate three primary cryosphere components into ESMs: ice sheets, sea ice, and permafrost (Giorgetta et al., 2013). Firstly, Greenland and Antarctic ice sheet models are coupled with ESMs, with ESM output downscaling guided by a regional climate model and the existing ice sheet model coupled to ESMs. Secondly, sea ice model processes are integrated to better represent the most vulnerable ice categories, such as interactions between waves and newly formed ice. Lastly, thermodynamics and moisture processes of permafrost are coupled within ESMs (Fig. 4). Meanwhile, observation data over mountainous glaciers have shown that ice-vapor interactions can decelerate the vanishing of glaciers by counteracting global warming and inducing localized cooling (Lin et al., 2021; Salerno et al., 2023).

Future ESMs should also consider the following cryospheric aspects: 1) Paleoclimate during glacial and interglacial periods (including rapid changes in the Eemian interglacial and the last glacial periods); 2) The cryosphere as a trigger for rapid climate change, which proposes incorporating near real-time or real-time cryospheric observational data into ESMs using machine learning or data assimilation methods; 3) Polar amplification of future warming, simulating future snow cover, permafrost, seasonal permafrost, glacier, sea ice, and ice sheet retreat; 4) Investigations into the mechanisms governing ice-vapor exchanges are crucial for refinement and advancement in ESMs.

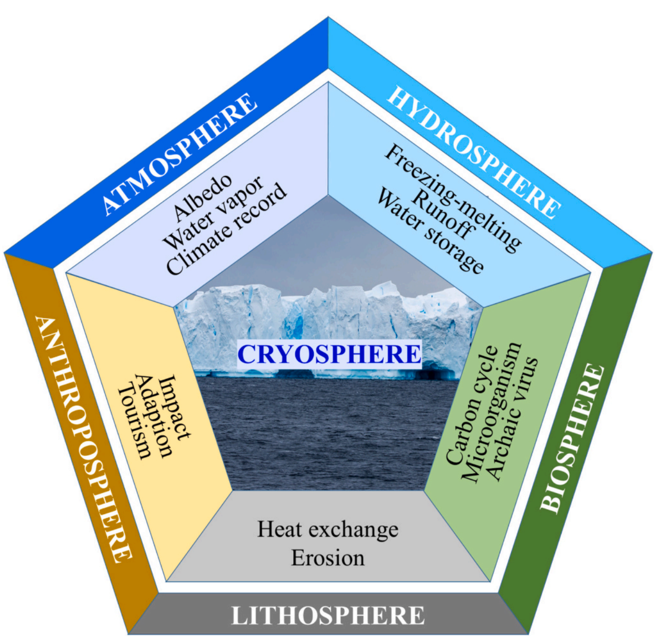

Fig. 4. The interactions between cryosphere and other spheres.

4.4. Dynamics framework for new generation ESMs

The dynamic core of an ESM is typically based on advanced numerical simulations of fluid dynamics, employing a combination of finite-difference and finite-element methods. It is specifically designed to model the intricate interactions between the Earth's mantle and core, encompassing heat transfer, material movement, and the generation of magnetic fields.

The dynamic core is a critical ESM component, significantly contributing to determining large-scale climate and geological patterns on Earth. The dynamic core is used to analyze the long-term development of Earth's climate and geology, as well as to forecast future alterations in the Earth system. This encompasses continental movement, mountain range formation, and the evolution of the Earth's magnetic field.

To enhance simulation efficiency and accuracy, the dynamics framework for new-generation ESMs has been designed using a modular approach, wherein separate modules represent different model components like the atmosphere, anthroposphere, lithosphere, and cryosphere, which can be interchangeably updated as new data becomes available.

One key feature of the dynamics framework is the use of adaptive mesh refinement (AMR) techniques, enabling higher resolution simulations in regions of interest while conserving computational resources in less active areas. This improves model accuracy by providing more detailed simulations of complex processes, such as weather patterns, ocean currents, and biogeochemical cycles.

Furthermore, the dynamics framework incorporates data assimilation techniques, allowing model calibration and validation against observational data. This is crucial for enhancing simulation accuracy and reducing uncertainties in model predictions.

Nonspecific models for simulating the interplay between Earth system components, such as atmosphere-ocean, land-ice, and biosphere, as well as enhanced models for simulating the carbon cycle and other biogeochemical processes, are all included in the framework.

Lastly, the dynamics framework has been designed to be flexible and scalable, facilitating integration with parallel computing architectures and high-performance computing platforms. This allows researchers to conduct larger, more complex simulations, explore previously inaccessible Earth system science domains, and augment the understanding of the Earth system.

4.5. Multi-resolution across various spatial-temporal scales in ESMs

Modeling multi-sphere interactions requires not only bridging different branches of science but also spanning various spatial and temporal scales (Johnson et al., 2023). As depicted in Fig. 5, numerous meso-scale phenomena occur between local and global scales, and these meso-scale events have the most direct impact on human activities. Examples of such phenomena include acid rain, floods, pollution, earthquakes, glacier movement, and nutrient cycling. Understanding and accurately modeling these meso-scale processes are essential for predicting their consequences on human societies and developing appropriate mitigation and adaptation strategies.

Research indicates that enhancing grid resolution may substantially augment modeling capabilities, as the effects of topography, land use, land-atmosphere interactions, and other crucial processes are more accurately captured (Bacmeister et al., 2014; ECMWF, 2016; Giorgi and Marinucci, 1996; Giorgi and Mearns, 1991; Leung and Qian, 2003). While global models are less prevalent than regional models, they offer benefits such as delivering global forecasts or simulations and circumventing numerical challenges related to lateral boundary conditions, which are significant sources of uncertainty in regional modeling and

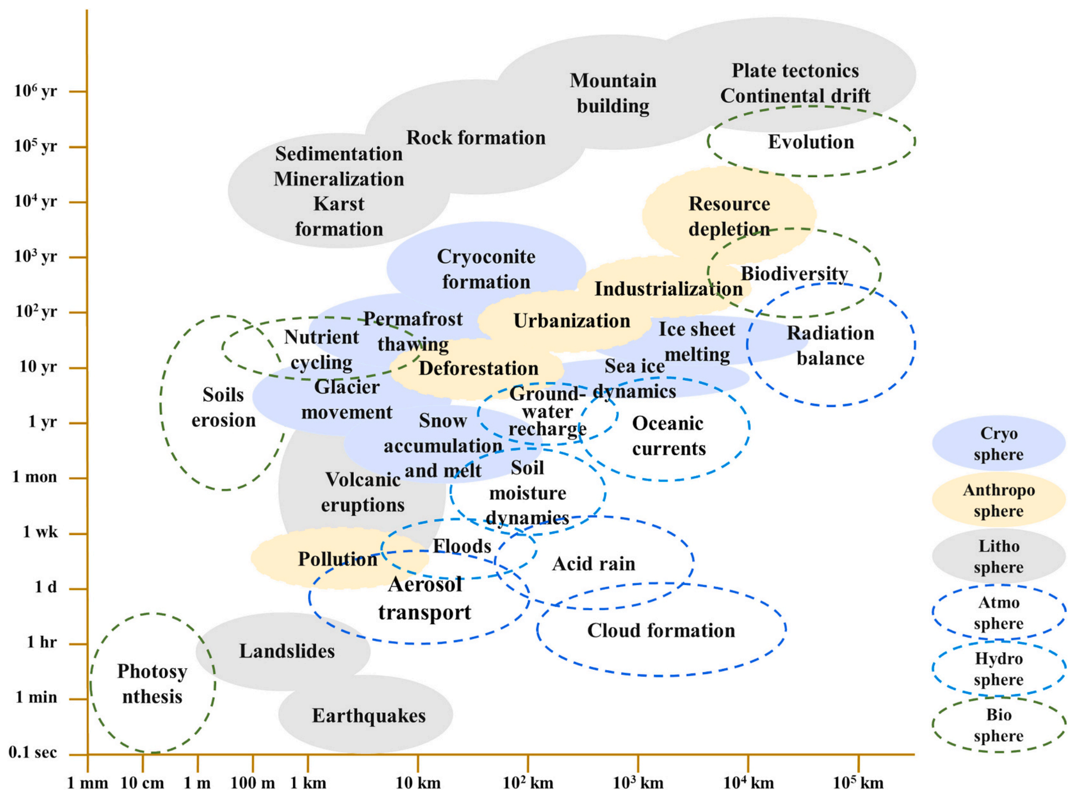

Fig. 5. Spatial-temporal scales for a variety of Earth processes (redrawn from Chang and Dickey (2001)).

restrict regional feedback to large-scale circulation (Giorgi and Mearns, 1991; Laprise, 2008; Leung et al., 2013; Wang et al., 2004; Prein et al., 2015; Xue et al., 2022; Xue et al., 2023).

In recent years, global hydrostatic variable resolution climate models, such as the variable-resolution version of the Community ESM, have been employed in various applications (Burakowski et al., 2019; Gettelman et al., 2018; Huang et al., 2016; Rauscher et al., 2013; Rhoades et al., 2016; Wang and Ullrich, 2018; Zarzycki et al., 2014, 2015). However, there is a scarcity of studies utilizing global non-hydrostatic variable resolution models for weather or climate simulations, particularly at convection-permitting scales (Prein et al., 2015; Zhao et al., 2019). Recent advancements in Earth System Modeling include the publication of a regional refined configuration for the E3SM V2 by Tang et al. (2023), which offers enhanced spatial resolution and improved representation of regional processes to be particularly noteworthy for the simulation of localized climate phenomena.

The selection of model resolution should be guided by a thorough understanding of the scales at which different processes operate. For example, processes such as convection, turbulence, and small-scale oceanic eddies benefit significantly from high-resolution modeling, as they are finely structured in both space and time. Conversely, larger-scale processes like global atmospheric circulation or deep ocean currents may be adequately represented at coarser resolutions. While high-resolution models can provide more detailed insights, they come with a substantial increase in computational demand. Therefore, a cost-benefit analysis is essential to balance the gain in model accuracy with the associated increase in computational resources. This involves assessing whether the added detail at higher resolutions leads to improved predictions or understanding that justify the extra computational expense. For example, some process models that require high-resolution simulation (such as flash floods, river temperature) are actually biased toward specific applications, while their feedback on other processes is not strong, which makes the loose coupling is enough. That is to say, not all processes require tight coupling; some modules can be apps within the ESM, and loose coupling is sufficient.

Advances in mesh generation have enabled the incorporation of spherical centroidal Voronoi tessellations (SCVTs) into a novel multi-scale modeling approach, known as the Model for Prediction Across Scales (MPAS), as noted by Du et al. (1999) and Ringler et al. (2008). In MPAS, the SCVTs facilitate local mesh refinement through a mesh generation process wherein a specified scalar density function dictates higher- and lower-resolution regions within the mesh (Ju et al., 2011). Meshes can be designed with multiple high-resolution areas, and elevated resolution in one area does not necessitate coarser resolution elsewhere. The underlying theory of SCVTs is robust regarding mesh properties and mesh generation. The atmospheric solver in MPAS (Skamarock et al., 2012) integrates non-hydrostatic equations, rendering it appropriate for both weather and climate simulations (i.e., for non-hydrostatic and hydrostatic flow simulations; Prein et al., 2015).

Meso-scale phenomena often elude resolution by GCMs and are too large to be disregarded in RCMs, necessitating the development of models that accurately simulate meso-scale phenomena within the Earth system. No single model can encompass all meso-scale effects; therefore, a diverse array of models is required, each possessing the fidelity to address a distinct set of questions. Significant advancements in research could be achieved by creating new models or interconnecting existing models, further pushing the upper-right quadrant of the plot while maintaining global extent (Johnson et al., 2023). Several approaches to model meso-scale phenomena in an ESM include:

1) High-resolution models: These models, with their elevated spatial resolution, can assist in capturing meso-scale phenomena. Although computationally intensive, progress in computing power has rendered them more feasible.
2) Downscaling: Employing downscaling techniques is one method for capturing meso-scale phenomena. This entails using a larger-scale model (e.g., a GCM) to supply boundary conditions for a smaller-

scale model (e.g., an RCM) more adept at capturing meso-scale phenomena.

3) Parameterization: Meso-scale phenomena can be modeled through parameterization, which involves representing their effects using simplified equations integrated into larger-scale models.
4) Data assimilation: Incorporating observational data into models can enhance their capacity to capture meso-scale phenomena. This may involve assimilating data from ground-based and satellite observations, as well as from other sources such as radar and lidar.

Temporal scales within the Earth system span from mere seconds to millions of years, presenting challenges for representation in ESMs. The intricate dynamics of the Earth system and its reactions to natural and human-induced alterations necessitate the modeling of a variety of earth system processes operating across various temporal scales. However, representing all these distinct temporal scales' processes and their interactions in ESMs necessitates a complex set of equations and models capable of capturing the dynamics of each Earth system component at various temporal scales. Several strategies can overcome current ESMs' limitations in simulating processes across different time scales, including enhancing computational power, broadening data sources, refining model physics and parameterizations, conducting model intercomparison, and developing superior model evaluation metrics.

Improving computational power: ESMs can leverage advancements in computing technology to simulate complex processes across various temporal scales. This may involve utilizing more sophisticated parallel computing techniques or harnessing cloud computing resources to augment the model's simulation capabilities.

Expanding data sources: To address limitations stemming from limited data sources, it is essential to broaden the range of data available to the model. This may entail acquiring additional observational data through satellites, ground-based sensors, or other sources, or employing advanced data assimilation techniques for data incorporation within the model.

Enhancing model physics and parameterizations: ESMs can overcome limitations related to simplifying assumptions or parameterizations by integrating more advanced model physics or parameterizations that more accurately represent the Earth System's complexities. For instance, utilizing sophisticated ocean mixing models can improve ocean circulation process simulations.

Model intercomparison: Conducting model intercomparison studies to evaluate different models' performance against each other can enhance the comparability of model outputs among various ESMs. This enables the identification of areas of agreement and disagreement between models, as well as highlighting areas for improvement in existing models.

Developing superior model evaluation metrics: Crafting better model evaluation metrics that capture the pertinent aspects of the Earth System can help assess ESMs' performance across various time scales. This may involve devising metrics more relevant to ecosystem processes or better suited for evaluating the model's performance over extended time scales.

In summary, overcoming the limitations of ESMs in simulating processes across different time scales necessitates ongoing research, development efforts, and collaboration among scientists, modelers, and data providers. Enhancing the accuracy and capabilities of ESMs can enable researchers to gain a more profound comprehension of the Earth System, and its reactions to both natural and human-induced alterations throughout history.

Advancements in computing technology enable ESMs to leverage increased computing power for simulating complex processes across a spectrum of temporal scales. This may involve utilizing advanced parallel computing techniques or capitalizing on cloud computing resources to augment the model's simulation capabilities.

As an example, Chen et al. (2021) emphasized the importance of concentrating on regional geographical characteristics that render localities unique, such as the Tibetan Plateau (TP). Notably, three aspects can be considered:

1) Geomorphology: The TP's high-altitude characteristics directly impact regional and global atmospheric circulation patterns.
2) Cryosphere-atmosphere interaction: The influence of cryosphere surface processes, including glaciers, permafrost, and snow, on the atmosphere should be considered. Glaciers and snow cover affect surface albedo, while permafrost melting influences the release of GHGs. Climate change reciprocally impacts cryosphere stability and governs the hydrological and ecological processes on the cryosphere surface.
3) Incorporating lithosphere and anthroposphere physical models into TP ESMs: This integration will surpass the boundaries of time, spheres, space, and disciplines.

The advancement of high-performance computers, model coupling technology, machine learning (ML), Artificial Intelligence (AI), big data analysis, and the internet of things presents an excellent opportunity to develop high-resolution regional ESMs with distinct features. By transcending time, sphere, space, and discipline boundaries among the atmosphere, cryosphere, anthroposphere, biosphere, and lithosphere, ESMs can capture these regional characteristics more accurately.

4.6. Physics and data as dual-drivers for ESMs

The Fourth Paradigm, with its emphasis on big data, presents both challenges and possibilities for the next generation of ESMs to capitalize on data integration and ML/AI techniques. These tools enable the integration of global observations and local high-resolution simulations in an ESM, allowing systematic learning from both sources (Fig. 6). However, to actualize such an ESM, scientific, computational, and mathematical challenges must be addressed, including the development of parameterizations amenable to automated learning and the design of learning algorithms suitable for ESMs.

Enhancing nearly all aspects of ESMs' main components is essential to better simulate the dynamic and physical processes of multi-spheres related to the Earth system's natural and human dimensions (Hantson et al., 2016). However, this approach is computationally intensive and demanding. Data-driven statistical/empirical models are employed to circumvent the incomplete physical understanding and computational limitations inherent in ESMs to satisfy practical requirements (Taylor et al., 2013). Although the data-driven approach boasts cost-effective development and implementation, it also faces challenges and limitations. These include issues related to data and data structure/quality for model training and evaluation, difficulties in determining comprehensive model prediction values, challenges in characterizing nonlinear and unsteady driver-response coupling relationships, and the lack of interpretability of prediction results.

Traditional statistical models utilized in prior studies (Chen et al., 2020; Hantson et al., 2020), such as Multiple Linear Regression and Autoregressive Integrated Moving Average models are more vulnerable than the rapidly developing ML and deep learning (DL) models (LeCun et al., 2015). The latter typically possess weaker model assumptions, exhibit less sensitivity to poor data quality, and demand larger data volumes and more complex model training processes.

Advancing scientific understanding and delivering reliable, high-quality Earth system predictions and data products necessitate securing adequate computational resources and utilizing state-of-the-art analytical capabilities. Several trends in Earth system simulation highlight the importance of powerful tools, effective technologies, and expanded computing and analysis capacities. These trends include increasing model complexity to enhance accuracy, pursuing higher resolution simulations and efficiency, employing ensembles to quantify uncertainty, and embracing the growing volume of data from new observation platforms (Silvern, 2022; Bi et al., 2023; Wang et al., 2023).

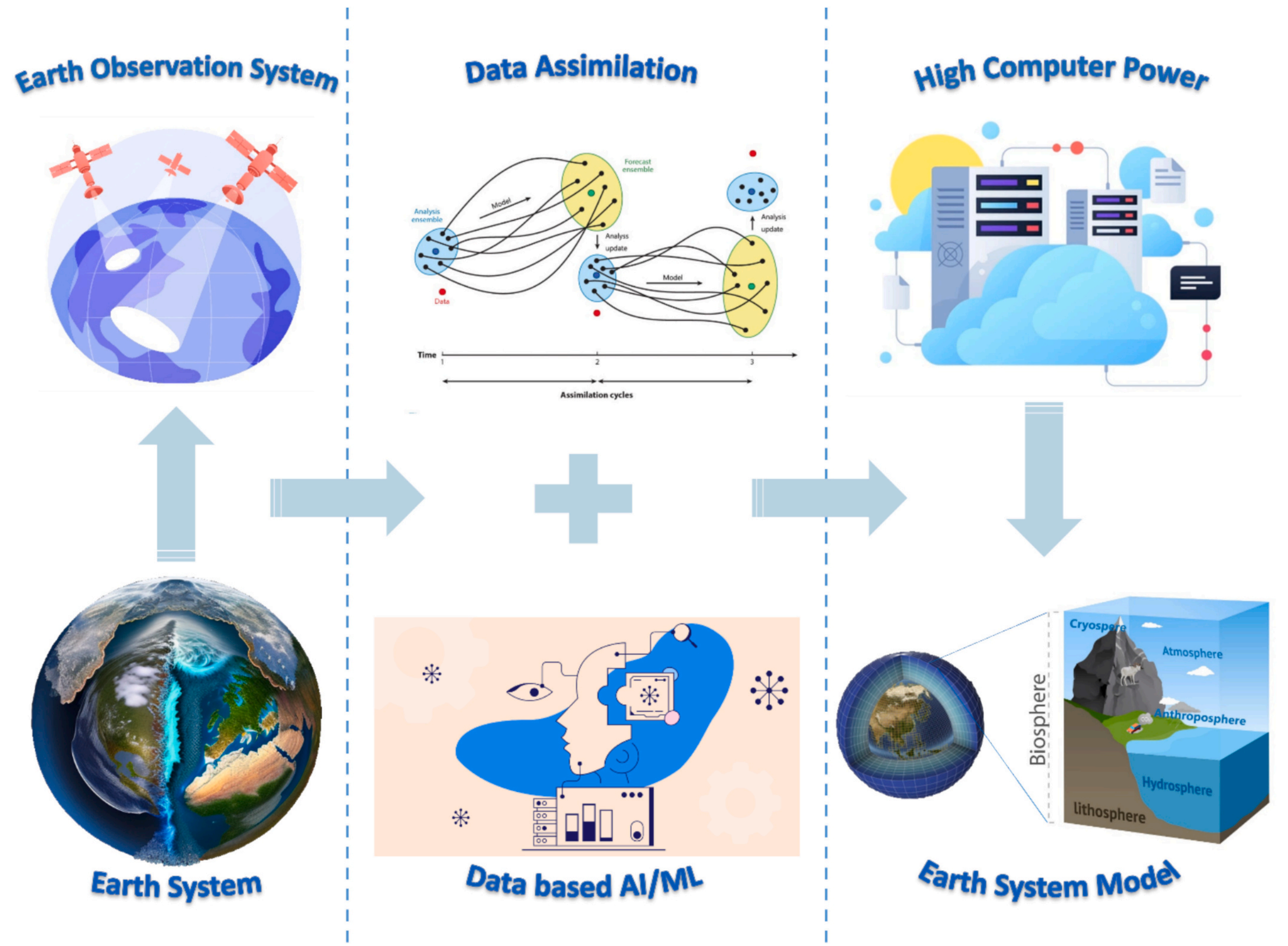

Fig. 6. Data-driven modeling vitalizes the ESM.

ML/AI offers the potential to improve various aspects of Earth system observation, modeling, analysis, prediction, understanding, and decision-making. These improvements may include optimizing automated simulation workflows, introducing novel methods for simulating and predicting physical system behavior, and refining the parameterization of physical and chemical processes. Although the Earth system science community has effectively utilized numerous statistical and modeling techniques, ML/AI technology can help transform computationally challenging problems into tasks that better exploit the continuous advancements in ML/AI computing optimization within information frameworks and computer architectures.

Such data-model fusion systems will enhance our ability to comprehend the complex Earth system by enabling hypothesis testing regarding Earth system functioning in previously inaccessible ways and providing more relevant societal predictions on timescales ranging from hours to decades (Gettelman et al., 2022).

4.7. Coupling of model components

The coupling strategies in ESMs, as more and more modules get involved, represents a critical challenge that directly impacts model accuracy and computational efficiency. Some particular challenges concern the frequency of coupling, the variables to exchange, and how we ensure robust feedback loops between components. First, we must well balance physical realism with computational constraints in determining the coupling frequency, where fast-evolving processes like atmosphere-land surface interactions require high-frequency coupling, while slower processes such as ocean biogeochemistry may permit lower-frequency coupling without significant accuracy loss. Second, we must carefully select variables to exchange between components, so as to capture essential interactions while avoiding redundant information transfer, focusing on primary state variables, flux variables, and derived quantities that mediate important feedbacks. Moreover, robust handling of feedback loops is essential for system stability and accurate representation of Earth system dynamics, requiring careful attention to dominant feedback mechanisms and proper process sequencing.

Modern coupling strategies often employ adaptive approaches that can dynamically adjust coupling frequencies, optimize data exchange patterns, and maintain conservation properties while allowing for different spatial and temporal resolutions between components. However, current coupling models face several significant challenges, including numerical instabilities at component interfaces, computational bottlenecks in data exchange, and difficulties in maintaining conservation properties across different spatial and temporal scales. Additionally, the increasing complexity of Earth system components, particularly with the inclusion of human systems and improved cryosphere representations, introduces new challenges in managing diverse timescales and process interactions. Moving forward, promising solutions include the development of more sophisticated adaptive coupling schemes that can automatically optimize exchange frequencies based on system states, improved numerical methods for handling multi-scale interactions, and new software frameworks that better support flexible coupling architectures. Machine learning approaches are also emerging as potential tools for optimizing coupling strategies and identifying key variables for exchange. Success in these areas will require continued collaboration between climate scientists, computational experts, and software engineers to develop more efficient and physically consistent coupling mechanisms that can handle the increasing complexity of ESMs while maintaining computational feasibility.

4.8. Balancing model complexity and usability

The growing complexity of ESMs creates a fundamental tension between scientific comprehensiveness and practical usability. As models incorporate more components and processes at higher resolutions, they become increasingly challenging to run, validate, and interpret. This complexity-usability balance requires careful consideration across multiple dimensions.

A key strategy for managing this balance involves implementing hierarchical model structures. These structures allow users to activate different levels of complexity based on their specific research needs. For instance, a policy analysis focusing on long-term climate projections might not require the same level of detail in cloud microphysics as a study of regional precipitation patterns. This modular approach enables users to match model complexity to their research questions while maintaining computational efficiency.

Computational efficiency can be enhanced through several approaches. Advanced numerical methods, including adaptive mesh refinement and mixed-precision computing, allow for targeted allocation of computational resources. Machine learning emulators can replace computationally expensive components when appropriate, particularly for well-understood processes. Additionally, developing efficient parallel computing algorithms and optimizing code implementation helps manage increasing model complexity.

To enhance usability, modern ESMs are incorporating improved user interfaces, standardized documentation, and automated diagnostic tools. These features help users navigate model complexity and interpret results effectively. Training programs and user support networks are also essential for building capacity within the scientific community. Furthermore, developing standardized outputs and visualization tools helps make model results accessible to policy makers and other stakeholders.

Looking forward, the development of ESMs should focus on “complexity by necessity” rather than “complexity by capability.” This means carefully evaluating whether adding new processes or increasing resolution genuinely improves model performance for intended applications. Regular assessment of model components’ contributions to prediction accuracy can help identify areas where complexity might be reduced without significant loss of performance.

Future opportunities for ESM development can be outlined as follows:

1) Integration of plate tectonic and paleogeographic models into existing ESMs through loose coupling, enriching the models’ representations of Earth’s geological history and processes.
2) Constructing a model of long-term human-environmental interaction, possibly through the utilization of agent-based modeling and game theory, to gain a more comprehensive comprehension and forecasting of the intricate interplay between natural systems and human actions.
3) To comprehend the far-reaching effects of climate processes on ice masses and other cryospheric components, ESMs must accurately quantify teleconnection impacts on the global cryosphere.
4) Introduction of multi-resolution across-scale techniques, allowing for high-resolution modeling in specific regions without necessitating the application of coarser resolution in other areas, thus improving the spatial representation and accuracy of models.
5) Advancing model-data fusion as a flexible system that facilitates various inquiries about the past and the inner workings of Earth systems (analysis), as well as predictions of future changes and impacts (prediction). This approach enables more comprehensive testing of hypotheses and improved understanding of Earth system processes.

5. Summaries

In this review, we have examined critical issues pertaining to the development of ESMs, shedding light on the inherent limitations and challenges that arise when ESMs endeavor to transcend temporal, spatial, and disciplinary boundaries across the intricate domains of the Earth system. The key challenges and limitations we’ve discussed include the history of the development of ESMs, the multifaceted landscape of challenges and future opportunities within ESMs, including vital components like the anthroposphere, lithosphere, and cryosphere, and the transformative potential of data-driven modeling in advancing ESM capabilities. Furthermore, we’ve explored the promising prospects presented by regional-scale Third Pole (TP) ESMs, underlining their significance in deciphering the driving forces behind Asian environmental changes. Our review contributes to the existing body of literature by addressing a notable gap, presenting a thorough analysis of the connections between climate models and other essential components of ESMs. In doing so, it furnishes readers with a deep and comprehensive understanding of the significance of data-driven modeling within the realm of Earth system science, along with its profound implications for understanding the dynamics of regional-scale environment.

In the future, the evolution of ESMs is set to embark on several pivotal trajectories directed toward augmenting their precision and efficiency. Foremost among these is the imperative integration of observations across diverse Earth system components, spanning the realms of the anthroposphere, biosphere, atmosphere, ocean, land, and cryosphere, enabling more refined simulations of component interactions and bolstering predictive capabilities. Furthermore, it is imperative that we prioritize the advancement of higher-resolution models designed to capture intricate interactions and processes. Leveraging cutting-edge computational techniques, including machine learning, holds the potential to illuminate hitherto undiscovered patterns and interrelationships among various Earth system components. Moreover, the future evolution of ESMs should encompass more comprehensive representations of biogeochemical cycles, including those of carbon, nitrogen, and phosphorus, thus enabling more accurate predictions of the Earth system’s responses to alterations in atmospheric composition and land use. Of paramount importance is the pursuit of establishing coupled human-ESMs, designed to comprehensively elucidate the intricate interplay between human activities and the various components of the Earth system. This crucial endeavor holds the promise of offering invaluable insights into the far-reaching consequences of human actions on the delicate equilibrium of our planet.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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