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COMMENTARY

A 1-km resolution global ocean simulation promises to unveil oceanic multi-scale dynamics and climate impacts

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As a crucial component of the Earth system, the ocean significantly impacts the climate due to its vast heat capacity, intricate multi-scale circulation, and considerable carbon storage capability. The ocean general circulation model (OGCM) is a numerical tool designed to solve the governing equations of oceanic fluid and thermal dynamics. It can simulate oceanic circulations and physical states, facilitating marine environmental forecasts and climate projections.[1]

The first OGCM was developed by Kirk Bryan in 1969, featuring a resolution of several hundred kilometers. Since the onset of the 21st century, advancements in numerical methods, high-performance computing, and physical oceanography have significantly enhanced ocean modeling. Consequently, the model has become increasingly complex, with more sophisticated dynamical cores and physical parameterizations, and additional ocean-related processes such as air-sea interactions, sea ice dynamics, and tidal effects.

THE CHALLENGE OF HIGH AND ULTRA-HIGH RESOLUTION

The horizontal resolution is essential for representing the developmental level of an OGCM, and the pursuit of higher resolution has been a persistent topic throughout the history of ocean modeling.[2]

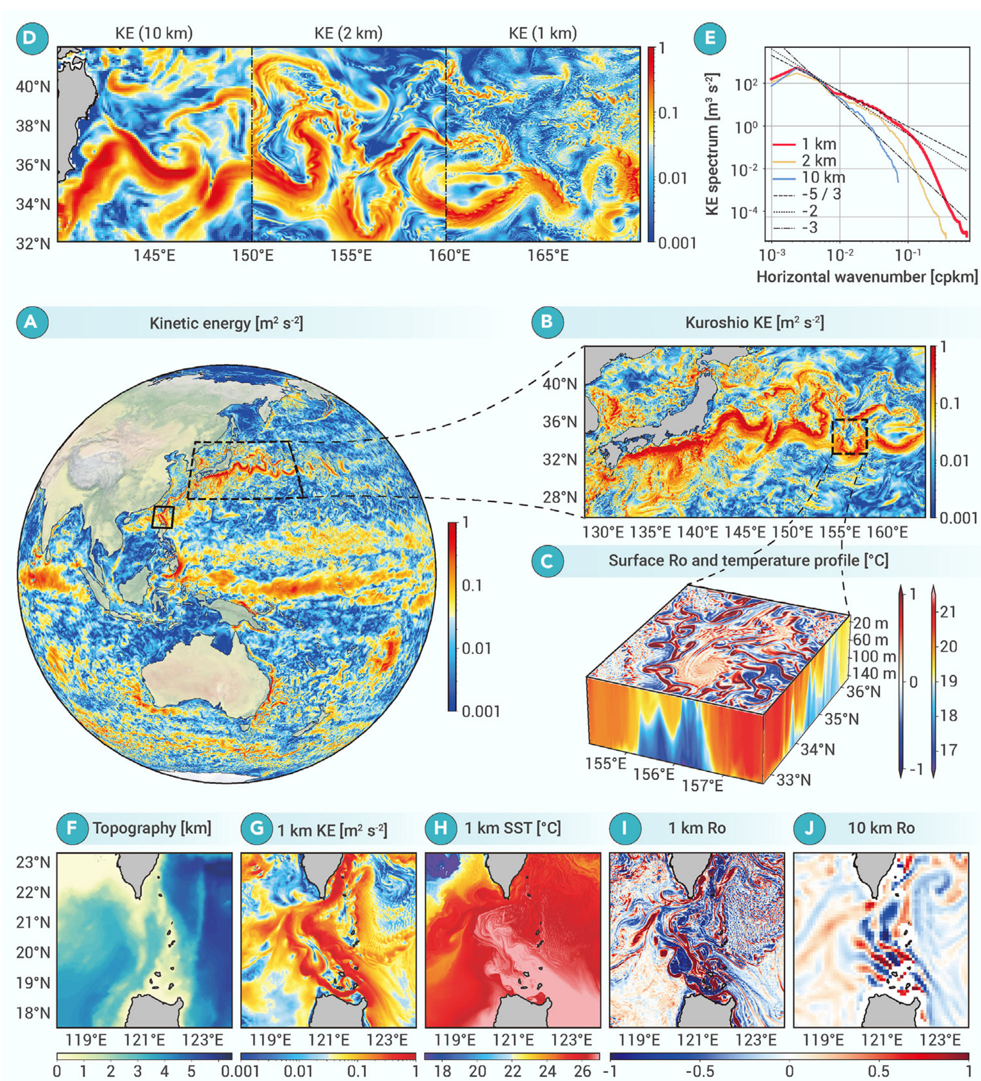

Figure 1. Snapshots of the LICOM global ocean simulation on January 19, 2016 (A) Surface kinetic energy (KE) from the global 1-km simulation. (B) A zoom-in of (A) on the Kuroshio Current and its extension. (C) An example of a mesoscale eddy indicated by the black box in (B), displaying the surface Rossby number (Ro) defined as the vertical component of relative vorticity normalized by the Coriolis parameter and upper-layer sea temperature on the side. (D) Surface KE in the Kuroshio Extension simulated at 10 km (left), 2 km (middle), and 1 km (right) horizontal resolutions. (E) The surface KE spectrum in the region. (F) Bathymetry in the Luzon Strait region. (G–I) Surface KE, temperature, and Ro from the 1-km simulation. (J) Surface Ro from the 10-km simulation. The initial fields are from the GLORYS12 version 1 reanalysis on January 1, 2016.

Conventionally, in the context of long-term global climate simulations, an OGCM is considered "high resolution" when its horizontal resolution reaches 10 km (0.1°). The primary motivation for achieving high resolution is to accurately capture oceanic mesoscale processes, which typically have spatial scales ranging from O(10 km) to O(100 km). These processes encompass the majority of the oceanic kinetic energy and substantially affect the intrinsic ocean dynamics and air-sea interactions, thereby essentially contributing to the Earth's climate variability. High-resolution OGCMs can capture most mesoscale activities in the open ocean at low- and mid-latitudes, leading researchers to refer to them as "eddy-rich" models. However, the oceanic submesoscale, characterized by spatial scales ranging from O(100 m) to O(10 km), can closely interact with the mesoscale, thereby playing a substantial role in the climate system.[3] To accurately describe the mesoscale dynamics, an ocean model must incorporate the effects of the submesoscale on the mesoscale. This presents a challenge that eddy-rich models often struggle to address.

Over the past decade, ocean models with kilometer-scale horizontal resolution have been burgeoning due to advancements in high-performance computing technology. To be distinguished from the traditional concept of "high-resolution" models, those with global average horizontal resolutions of less than 5 km are now classified as "ultra-high-resolution" models. They can fully cover the oceanic mesoscale range and capture a significant portion of oceanic submesoscale phenomena, which can closely interact with mesoscale processes through the inverse energy cascade, thereby playing a substantial role in the climate system. Ultra-high resolution OGCMs can reduce the uncertainty associated with parameterization schemes and enhance simulation fidelity, enabling more detailed studies of local processes (e.g., eddy and wavy motions) and their multi-scale interactions. These insights can guide the configuration of eddy-rich models, resulting in improved climate projections and marine environmental forecasts, particularly for high-impact, low-probability extreme events.

However, developing ultra-high-resolution models is highly challenging. The need for massive computing and storage resources makes it essential for the model to be ported onto high-performance computers with heterogeneous architectures. Developing efficient and stable parallel communication and I/O technologies, adopting customized acceleration solutions, and achieving performance portability and scalability are critical for advancing these models.

THE GLOBAL OGCM

The world's oceans form a connected system, interlinking through inter-basin circulations that can be naturally represented in global OGCMs. This study reports the preliminary findings of a global OGCM at a horizontal resolution of 0.01°. It has a minimum grid spacing of 0.27 km, a maximum grid spacing of 1.15 km near the equator, and a typical grid spacing of 0.8 km in mid-latitudes. For simplicity, we refer to it as global 1-km resolution. Before this work, the highest resolution achieved by a global OGCM with scientific results was 1.25 km.[4] Therefore, this study addresses the final gap in kilometer-scale horizontal resolution for global OGCMs and marks the first instance of a global 1-km OGCM yielding scientific results (Figure 1A).

The LASG/IAP Climate System Ocean Model (LICOM) is a global OGCM that has participated in the recent Coupled Model Intercomparison Project and the Ocean Model Intercomparison Project. We present the results of global ocean simulations using the version that has been the finalist of the 2024 ACM Gordon Bell Prize for Climate Modelling.[5] Wei et al.[5] discuss the breakthroughs of LICOM in high-performance computing, including achieving performance portability across nearly all types of supercomputers listed in the TOP500, demonstrating strong performance scaling across heterogeneous architectures, and attaining over 1 SYPD on both the Sunway and ORISE supercomputers at global 1-km resolution. Unlike Wei et al.,[5] we here focus on the scientific implications.

THE GLOBAL 1-KM RESOLUTION EXPLOSIVELY BOOSTS SUBMESOSCALES

The most notable feature of the global 1-km horizontal resolution model is its capacity to simulate submesoscale processes. The 1-km simulation effectively captures submesoscale perturbations along the meandering jets, around mesoscale eddies, and between mesoscale entities (Figure 1B). The surface Rossby number (Ro), which quantifies the abundance of submesoscale signals, exhibits a blooming coronal structure associated with the mesoscale eddy (Figure 1C). The submesoscale motions surrounding the mesoscale eddy exhibit a high Ro and are linked to elevated vertical heat transport in the upper ocean. Compared with the 10-km and 2-km simulations (Figure 1D), the 1-km simulation shows a dramatic enhancement in representing submesoscale features, particularly braid-like structures within the vigorous flow. The surface kinetic energy spectrum (Figure 1E) also reveals spectral slopes indicative of surface quasigeostrophic dynamics with (-2) and without ($-5/3$) ageostrophic advection.

THE GLOBAL 1-KM RESOLUTION EFFECTIVELY CAPTURES TOPOGRAPHIC EFFECTS

The ultra-high-resolution OGCM can accurately depict bathymetry and coastlines. For example, the Luzon Strait region features a chain of islands along with irregular underwater ridges and seamounts (Figure 1F), which complicate the flow patterns. The global 1-km simulation reveals abundant submesoscale activities in the Luzon Strait, including narrow meandering jets (Figure 1G), submesoscale filaments (Figure 1H), and vigorous submesoscale eddies within the topographic wakes (Figure 1I). The joint effect of a more realistic bathymetry and a finer model grid allows the global 1-km model to capture flow details and realism that far exceed those of the global 10-km eddy-rich model (Figure 1J).

SUMMARY AND PROSPECT

The results highlight the immense potential of ocean models at global 1-km resolution to unveil oceanic multi-scale dynamics and promote our understanding of the climate system via long-term simulations. Furthermore, the model can advance Earth system climate modeling and marine environmental operational forecast by coupling with other components (e.g., the high-resolution atmospheric model) to foster a comprehensive understanding of multi-spherical interactions (e.g., carbon cycle), and to support the establishment of a sustainable Blue Economy. The model can also contribute to developing a Digital Twin of the Ocean and a big data system by providing datasets that include physical variables with detailed spatiotemporal variations. These applications will assist researchers in conducting thorough ocean studies and aid decision-makers in managing ocean resources intelligently and efficiently.

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DECLARATION OF INTERESTS

The authors declare no competing interests.