Multi-scale and Multi-layer Ocean Processes and Their Interactions: A Successful Case Study for El Niño Simulation (Postprint)

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Abstract

The ocean hosts various multi-scale natural phenomena that exert significant influences on climate and environment, such as tropical instability waves and El Niño-Southern Oscillation (ENSO). These phenomena represent integrated products of processes occurring at different temporal and spatial scales within the ocean and their interactions with other spheres of the Earth system, exhibiting characteristics of complexity, diversity, variability, and interaction. Ocean research must be conducted as a systematic endeavor to account for interactions and feedbacks among multi-scale and multi-sphere processes; it should employ integrated approaches combining different methods (including observations, theory, and models); and based on the understanding and representation of phenomena and processes, further construct models to simulate, predict, and project ocean-related phenomena and their impacts on climate and environmental changes. As the strongest interannual variability signal in the Earth system, the ENSO phenomenon constitutes the core content for studying interannual timescale air-sea interactions and climate projection. This paper takes ENSO as an example to elucidate the modulating effects of oceanic multi-scale and multi-sphere processes and their interactions on ENSO (such as the feedback effects of marine organism-induced heating and tropical instability waves).

Full Text

Studies on Multi-scale and Multi-sphere Processes in the Ocean and Their Interactions: A Successful Example Applied to El Niño Simulation

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Abstract

The ocean hosts various multi-scale natural phenomena that significantly influence climate and environment, such as tropical instability waves and the El Niño-Southern Oscillation (ENSO). These phenomena represent integrated products of oceanic processes across different temporal and spatial scales and their interactions with other spheres in the Earth system, exhibiting characteristics of complexity, diversity, variability, and interaction. Ocean research must be conducted systematically to account for interactions and feedbacks among multi-scale and multi-sphere processes, employing integrated approaches that combine observations, theory, and modeling. Based on understanding and characterizing these phenomena and processes, models can be constructed to simulate, predict, and project ocean-related phenomena and their impacts on climate and environmental changes. As the strongest interannual variability signal in the Earth system, ENSO represents the core content for studying interannual-scale ocean-atmosphere interactions and climate projection. This paper uses ENSO as an example to illustrate the modulating effects of multi-scale and multi-sphere oceanic processes and their interactions on ENSO, such as feedbacks from ocean biology-induced heating effects and tropical instability waves.

Keywords: multi-scale and multi-sphere processes in the ocean, oceanic observations, oceanic simulations, El Niño-Southern Oscillation (ENSO)

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The ocean covers approximately three-quarters of the Earth' s surface and constitutes a key component of the Earth system. Due to its enormous water volume and heat capacity, as well as the thermal inertia and slow mobility of seawater, the ocean makes important contributions to global heat budgets, water cycles, and carbon cycles, playing a crucial role in climate changes across various timescales (interannual, decadal, and long-term trends). In particular, the ocean serves as the carrier of long-term memory in the climate system and represents the root of climate predictability. Ocean science is an interdisciplinary field that describes seawater properties and their movement patterns while recognizing spatiotemporal evolution laws in the ocean. In-depth research on multi-scale processes related to ocean-climate-environment interactions and interconnections among various spheres (such as the biosphere and atmosphere) constitutes a major international frontier topic in contemporary ocean and climate science, forming the foundation and focus for predicting and responding to climate and environmental changes.

1. Multi-scale and Multi-sphere Processes in the Ocean and Their Interactions

Oceanic changes can be categorized into natural variability and changes induced by external forcing. Natural variability arises from exchange processes and interactions among multiple spheres within the Earth’ s natural climate system, including the ocean, land, sea ice, and atmosphere. External forcing factors include human activities (such as increased greenhouse gases, anthropogenic aerosols, and large-scale land use/cover changes) that produce global and regional effects (such as sea level rise and ocean acidification). The ocean contains various multi-scale natural phenomena that significantly impact climate and environment, playing important roles in the formation and variation of climate modes across different timescales. Oceanic variations can lead to persistent regional and global climate changes across interannual, decadal, or longer timescales (including physical, biological, and chemical aspects).

A typical example is ENSO, generated by ocean-atmosphere interactions in the tropical Pacific [1,2], which represents the strongest interannual climate variability mode involving tropical upper-ocean dynamics. Longer-term decadal climate variability modes (such as the Atlantic Meridional Overturning Circulation) are global-scale phenomena involving the deep ocean (influenced by oceanic thermohaline circulation) and constitute important causes of decadal climate variability in many regions worldwide. For instance, the Pacific Decadal Oscillation is considered a major reason for the recent global warming slowdown or hiatus since the beginning of the 21st century. Climate change on centennial timescales is primarily determined by human activities, particularly the warming effects of CO increase—research indicates that human activities have increased CO levels, significantly altering global climate and environmental states in terms of long-term trends. Of course, natural climate variability and anthropogenic changes interact with each other, and observed climate changes represent integrated products of multi-scale processes. Understanding these complex interactions requires profound knowledge of climate dynamics, particularly global-scale ocean circulation dynamics, and necessitates developing new theories to elucidate interactions among processes across different timescales.

ENSO is an interannual climate change phenomenon dominated by oceanic processes in the tropical Pacific. This paper will illustrate the modulating effects of multi-scale and multi-sphere oceanic processes and their interactions on ENSO by examining their impacts, summarizing the current status and future development trends in this field. ENSO originates from interactions among sea surface atmospheric wind fields, sea surface temperature fields, and oceanic thermoclines in the tropical Pacific—namely, the so-called thermocline feedback mechanism. In addition to this dominant factor, multi-scale and multi-sphere processes in the tropical Pacific can modulate ENSO, such as ocean biology-induced heating (OBH), tropical instability waves (TIWs), freshwater flux (FWF) at the air-sea interface, and forcing and feedback processes from tropical cyclones (TCs). These processes are directly influenced by ENSO on one hand, while their induced changes can, in turn, modulate ENSO characteristics (i.e., feedback). Moreover, these different-scale and different-sphere processes interact with each other, and their combined effects on ENSO lead to ENSO' s diversity, variability, and complexity, further contributing to forecast uncertainties. Therefore, comprehensive approaches combining observations, theory, and modeling are needed for systematic research.

2. Acquisition and Application of Ocean Observational Data

The purpose of ocean observation is to obtain data on oceanic element fields (including physical, chemical, and biological processes or phenomena), reveal their spatiotemporal distribution characteristics and variation patterns, and provide basic state variable information and scientific basis for ocean scientific research, marine resource development, and marine disaster forecasting. Observation methods and forms have evolved from early single-form observations or monitoring (such as coastal stations, island stations, floating/submerged buoys, and ship-based surveys) to diversified, systematic, and three-dimensional observation systems or networks combining land-based, sea-based, and space-based platforms (such as in-situ or remote sensing observational data). Particularly, targeted intensive ocean observations can be conducted around specific oceanic phenomena and processes (including development and use of new measurement instruments, design of optimized observation schemes or networks, and exploration of new data analysis methods).

Driven by ocean technology, modern observational techniques have provided extensive multi-source oceanic data, accumulating more refined and longer-term ocean observational data (such as continuously expanding spatiotemporal scales of ocean processes described based on observations, currently developing into long-term observations of mesoscale processes, sub-mesoscale process observations, and microscale process observations within the ocean or at the air-sea interface). Driven by the demands of interdisciplinary research, synchronous observational data on multi-element interdisciplinary oceanography are also continuously accumulating [3], providing comprehensive, high spatiotemporal resolution ocean observational data. In particular, Argo (the global ocean observation program) has provided ocean subsurface observational data for human use in various applications in recent years.

Ocean observational data have been widely applied. Beyond describing the four-dimensional spatiotemporal evolution characteristics of oceanic element fields, they have been used to construct and validate the effectiveness of parameterization methods for multi-scale and multi-sphere processes in the ocean, as well as to test the accuracy of model simulations and predictions. For example, based on systematic observational analysis and through understanding oceanic physical processes and mechanisms, the overall representation of ocean environment forecasting models can be improved to enhance simulation and prediction skills. By assimilating ocean observational data, the oceanic initial state in numerical forecasting systems can be improved or optimized to overcome current limitations in understanding oceanic physical processes and the potential impacts of other uncertainty factors on environmental forecasting accuracy.

Although ocean observation has made considerable progress, obtaining ocean observational data remains extremely expensive and time-consuming. Relative to the vast ocean, the spatiotemporal distribution of ocean observational data remains extremely uneven. The difficulty of ocean observation conditions leads to limitations and serious deficiencies in understanding oceanic processes, necessitating research approaches that combine observations with modeling.

3. Development and Improvement of Comprehensive Ocean Models

Based on understanding and characterizing processes, constructing numerical models and simulations based on physical laws represents a powerful tool for studying multi-scale and multi-sphere processes in the ocean and their interactions. Over the past half-century, models and simulations have made tremendous progress, providing us with opportunities for comprehensive and profound understanding of oceanic multi-scale and multi-sphere processes, mechanisms, evolution patterns, and future changes. For example, models have evolved from early ocean-atmosphere coupled models to climate system models considering more Earth system components (such as sea ice), and further to Earth system models incorporating biogeochemical processes. Meanwhile, model development has fully utilized observational data for further improvement and refinement, with models also providing a core platform for observational data applications. For instance, data assimilation combining models and data can determine optimal ocean states and parameter values. In particular, Earth system models including the ocean serve as integrated tools for seamless simulation and forecasting of weather-climate-environment, capable of not only reproducing past global climate evolution but also projecting future climate changes. Therefore, the development and improvement of comprehensive models based on multi-scale and multi-sphere coupling have important scientific and strategic significance.

Due to the scarcity of ocean observational data and the characteristics of multi-scale and multi-sphere processes, the developed comprehensive models are extremely complex and computationally intensive. Therefore, ocean observation design itself must be scientific and optimized; observational data utilization must be reasonable and effective; integration of observational data and models must be coordinated and consistent; and effective use of observational data is needed to construct parameterizations of multi-scale and multi-sphere processes that models cannot resolve. These methods and concepts have been widely applied in research on ocean-atmosphere interactions and ENSO.

ENSO is primarily driven by ocean-atmosphere physical processes in the tropical Pacific and has significant impacts on multi-scale and multi-sphere processes in the ocean, such as triggering anomalies in marine ecosystems. The induced marine ecological responses further feed back on physical processes, generating interactions between ocean physics and biology. Currently, climate models cannot reasonably represent marine biological processes and their feedback effects, requiring the use of observational data to develop parameterization schemes to represent the impacts of ocean biology-induced heating effects on ENSO.

4. Modulating Effects of Multi-scale and Multi-sphere Processes on ENSO

ENSO is the most significant interannual climate variability signal in the Earth system. Occurring in the tropical Pacific, it exerts major global influences on weather and climate through atmospheric teleconnections. Decades of extensive and in-depth ENSO research have made tremendous progress, with current real-time forecasting extending six months to one year ahead (see the International Research Institute for Climate and Society website at Columbia University: http://iri.columbia.edu/climate/ENSO/currentinfo/update.html). The intermediate coupled model developed and improved by the Institute of Oceanology, Chinese Academy of Sciences (IOCAS ICM) provides monthly ENSO real-time forecasting results for the international academic community (Figure 1 [Figure 1: see original paper]) [4,5]. However, due to the tremendous variability and diversity in ENSO' s spatiotemporal evolution, many challenges remain in ENSO research. The mechanisms of its variations are still unclear, simulation errors for sea surface temperature (SST) in the tropical Pacific region with major impacts remain large, and real-time ENSO forecasting exhibits considerable uncertainty and inter-model differences, failing to meet actual needs for disaster prevention and mitigation. Particularly since the 1990s, the frequent occurrence of different types of El Niño events has made ENSO spatiotemporal evolution processes more complex and variable, posing greater challenges to real-time forecasting skill.

Studying ENSO formation mechanisms and accurately forecasting the occurrence, development, and transition processes of ENSO events in a timely manner constitutes a key topic in climate dynamics and one of the most promising approaches for exploring interannual-scale climate forecasting. It is currently a hotspot of concern for the scientific community, government agencies, and the public, possessing not only important scientific significance but also potentially enormous economic and social value.

Clearly, the ENSO process involves interactions among different timescales, mutual constraints among multiple forcing and feedback processes, influences from cross-regional ocean-atmosphere processes, and atmospheric stochastic processes. For example, ENSO originates in the tropical Pacific. In addition to the thermocline feedback mechanism, other multi-scale and multi-sphere processes exist in the tropical Pacific (Figure 2 [Figure 2: see original paper]). Beyond these specific processes, interactions among different timescale processes (such as the annual cycle, intraseasonal oscillations, quasi-biennial oscillations, and low-frequency variability) can modulate ENSO, making its spatiotemporal evolution more complex and variable. For instance, under global warming background, large-scale ocean-atmosphere mean climate fields have changed. Since the beginning of the 21st century, the background state of the tropical Pacific has shown significant decadal changes, specifically manifested as: persistently strengthening tropical Pacific trade winds, warming of intermediate-layer seawater in the western Pacific, strengthening of equatorial eastern Pacific cold water upwelling, and decreasing tropical eastern Pacific SST. These background field changes can also alter ENSO' s natural characteristics, leading to different types of El Niño events and exacerbating asymmetry between the two phases of the ENSO cycle. For example, from the early 21st century to 2014, La Niña events could persist for multiple years, while El Niño phenomena rarely occurred in the equatorial eastern Pacific, being replaced by El Niño events mainly occurring in the central equatorial Pacific; whereas during the 1980s-1990s, the opposite situation occurred [6]. On the other hand, these background field changes modulate global warming (for example, slowing the upward trend of global mean temperature). Some studies have indicated that the Pacific ocean-atmosphere coupling system modulates global warming, and the asymmetric development of ENSO at interannual timescales and its cumulative effects can lead to decadal SST changes in the central equatorial Pacific, which can modulate global warming impacts. However, many unresolved scientific questions remain, including ENSO decadal variability and the mutual influences between decadal climate change and global warming.

4.1 Modulating Effects of Multi-scale Ocean Processes on ENSO—An Example of Tropical Instability Waves

An important ocean-atmosphere process in the tropical eastern Pacific region is tropical instability waves (TIWs). High-resolution satellite observational data indicate that along the cold tongue region near 3°N in the tropical eastern Pacific, there exists a distinct sea surface temperature front that separates the near-equatorial upwelling cold water region from the warm water region to its north. Due to meridional shear instability of major equatorial currents and baroclinic instability of oceanic temperature fronts, disturbances are generated in the cold tongue region of the tropical eastern Pacific and propagate westward as waves—this phenomenon is called TIWs. Although TIWs are a mesoscale to small-scale phenomenon, they can significantly influence interannual climate variability (such as ENSO), reflecting interactions among multi-scale processes. For example, this mesoscale phenomenon originating from oceanic internal processes can significantly impact heat and momentum balances in the tropical eastern Pacific through horizontal transport and vertical mixing in the upper ocean, thereby affecting the climatic mean state and its seasonal and interannual variations in the tropical region. Some studies have pointed out that the meridional heat transport toward the equator generated by TIWs-induced vertical mixing can exceed sea surface heat flux values. Satellite observational data analysis shows that SST perturbations caused by TIWs in the equatorial eastern Pacific cold tongue region can induce systematic responses in sea surface wind fields, clouds, and precipitation. SST perturbations caused by TIWs in the tropical eastern Pacific can reach 2–3°C, with accompanying sea surface wind speed changes reaching 20%–30% of climatological mean values, and wind stress vorticity and divergence changes reaching their climatological mean values [7]. Therefore, TIWs can exert important influences on the climatic mean state, seasonal variations, and large-scale interannual variability in the equatorial eastern Pacific cold tongue region.

In recent years, satellite observational data providing high-resolution ocean-atmosphere data have enabled substantial progress in TIWs research. However, current climate models cannot represent such mesoscale to small-scale processes as TIWs, particularly the wind field effects induced by TIWs, which are not well represented in current large-scale ocean-atmosphere coupled models. In previous work [7], an empirical model for calculating TIWs-induced wind fields was constructed using satellite observational data and applied to oceanic and ocean-atmosphere coupled models. Simulation results showed that low-level atmospheric wind fields generated by TIWs have considerable impacts on both the climatic mean state and interannual variability of sea temperature in the tropical eastern Pacific (particularly for La Niña events), demonstrating that mesoscale to small-scale processes such as TIWs can also feed back on large-scale processes like ENSO (Figure 3 [Figure 3: see original paper]). However, current analyses and simulation experiments on TIWs-induced wind field forcing and feedback effects are quite preliminary, and no studies have yet examined their impacts on ENSO forecasting. Further detailed research is needed on the role of TIWs in ocean-atmosphere coupled models and their feedback processes on ENSO, as well as assessment of TIWs' impacts on large-scale ENSO phenomena, processes, and forecasting.

4.2 Modulating Effects of Multi-sphere Ocean Processes on ENSO–An Example of Ocean Biology-Induced Heating Effects

ENSO is primarily controlled by physical processes but is also modulated by some multi-sphere processes. Here we provide an example of multi-sphere processes and their feedback effects. Recent studies have shown that interactions exist between marine biology and physics in the tropical Pacific, which can subsequently influence ENSO characteristics. On one hand, ENSO-related physical processes control marine biological conditions in the tropical Pacific; on the other hand, the presence and variability of upper-ocean phytoplankton biomass, in turn, modulate the vertical penetration of solar radiation in the upper ocean, thereby causing ocean biology-induced heating and feedback effects on oceanic physical processes, forming interactions among marine biology, physics, and climate. For example, the impact of marine biology-induced heating effects on physical processes can be described by the vertical penetration of solar radiation in the upper ocean, which can be simply characterized by introducing a penetration depth variable (Hp) as the main linking variable between ocean physics and marine ecosystems in the climate system. At the tropical Pacific basin scale, Hp exhibits interannual variability closely related to the ENSO cycle, regulating the transmission of solar radiation in the upper ocean and playing an important role in the mixed-layer heat budget. Studies have found that interannual variability of ocean biology-induced heating in the tropical Pacific can provide negative feedback to ENSO. Therefore, in diagnostic and simulation studies, the climate feedback caused by ocean biology-induced heating must be fully considered. However, current tropical Pacific basin-scale models and global ocean-atmosphere coupled models still have great uncertainties in representing ocean biology-induced heating effects and marine biology-climate interactions, particularly in realistically simulating Hp interannual anomalies induced by ENSO in integrated models incorporating ocean physics, biology, and chemistry components. Currently, data describing marine biological and chemical states are very scarce.

Meanwhile, satellite observations provide unprecedented basin-scale ocean color data, making it possible to describe marine ecological processes and marine biology-climate interactions. For example, satellite observational data have been used to derive an empirical model characterizing Hp interannual variability in the tropical Pacific, which was embedded into an ocean-atmosphere coupled model to represent ocean biology-induced heating effects and marine biology-climate interactions [8]. Results showed that ocean biology-induced heating effects have substantial modulating impacts on ENSO (Figure 4 [Figure 4: see original paper]). However, more in-depth research is needed on the relationship between marine ecological processes and ENSO, combining existing observational and simulation data, particularly assessing the impacts of multi-sphere processes (including marine ecology-induced heating effects) and their interactions on ENSO forecasting. This section also provides an example of how to use satellite data to characterize this feedback process to improve ENSO simulation in ocean-atmosphere coupled models.

5. Conclusion

As ocean-related global climate and environmental changes concern the future and destiny of all humanity, the importance and urgency of ocean scientific research have risen to unprecedented heights. Ocean research involves multi-scale processes and interactions with other spheres in the Earth system (such as air-sea interfaces, land-sea interfaces, and seabed interfaces), exhibiting complexity, diversity, and variability. Currently, ocean research faces tremendous challenges and difficulties. Ocean studies should adopt an Earth system perspective, conducting frontier comprehensive research on interactions between the ocean and other spheres (such as the atmosphere, hydrosphere, biosphere, and lithosphere). Integrated approaches combining observations and modeling should be employed to promote the establishment, improvement, and perfection of multidisciplinary cross-observation and simulation systems, conducting prediction and projection research on future ocean, climate, and environmental changes to provide important scientific and technological support for national strategies of "Maritime Power" and the "21st Century Maritime Silk Road."

ENSO is the most important product of tropical Pacific ocean-atmosphere interactions and the most predictable interannual variability signal in the Earth system. Studying ENSO formation mechanisms and accurately forecasting the occurrence, development, and evolution of ENSO events in a timely manner has tremendous economic value. Therefore, ENSO and its tropical ocean-atmosphere interaction research constitute a frontier topic in contemporary climate dynamics. Although great achievements have been made in ENSO research, accurate and real-time prediction of its entire occurrence and development process remains elusive. While the main ocean-atmosphere processes triggering ENSO events (i.e., the thermocline feedback mechanism) are well understood and can be simulated, understanding of multi-scale and multi-sphere processes in the tropical Pacific and their modulating effects on ENSO remains limited, and current models cannot or have not adequately represented these processes. As examples, this paper presented the roles of ocean biology-induced heating processes and TIWs in modulating ENSO to demonstrate ENSO's diversity and variability resulting from modulation by multi-scale and multi-sphere oceanic processes.

To address major scientific issues urgently needing resolution as China moves toward deep oceans (such as ENSO modulation mechanisms and real-time ENSO forecasting), concentrated efforts should be made using Earth system coupled models as tools and numerical simulation as the main approach, focusing on ENSO. We should actively establish and improve the Western Pacific Ocean observation network to monitor ENSO phenomena and processes in real time, while conducting research on multi-scale and multi-sphere process interactions (such as developing and improving multi-sphere coupled models including ocean and atmosphere), combined with ocean data assimilation techniques to improve real-time ENSO event forecasting and short-term climate prediction.

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