Development of a global high-resolution marine dynamic environmental forecasting system

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ABSTRACT

A project entitled ‘Development of a Global High-resolution Marine Dynamic Environmental Forecasting System’ has been funded by ‘The Program on Marine Environmental Safety Guarantee’ of The National Key Research and Development Program of China. This project will accomplish its objectives through basic theoretical research, model development and expansion, and system establishment and application, with a focus on four key issues separated into nine tasks. A series of research achievements have already been obtained, including datasets, observations, theories, and model results.

1. Introduction

A global numerical forecasting system with a nominal horizontal resolution of 1/4° in ocean environments was initially constructed at the National Marine Environmental Forecasting Center (NMEFC), Beijing, China, during 2010–15, supported by China’s twelfth Five-Year Plan for Science and Technology Support. The system included numerical ocean wave, circulation, and tidal forecast models with data assimilation. The forecasting products released by the system played an important role in marine and emergency-response services (Wang et al. 2016). The ocean forecasting systems of the GODAE national members (Schiller et al. 2012) planned several improvements during the next few years, including a higher model-grid resolution (horizontal and/or vertical), development of a biogeochemical model coupled with the physical system, implementation of coupled ocean–wave–ice–atmosphere forecasting systems, improvement of the data assimilation scheme to adapt to the characteristics of the new forecasting systems, assimilation of new observational data, introduction of an ice component into relevant systems, resolving the tidal signal, and better diagnostic protocols (Tonani et al. 2015). However, to be competitive with other advanced ocean forecasting systems, the numerical prediction technology of the global operational marine dynamic environment in NMEFC should be improved. This will enhance the model resolution and the parameterization of physical processes, thus enabling the representation of mesoscale phenomena in the ocean. In recent years considerable improvements in the technology of observational science, theoretical research, numerical models, and forecasting applications pertaining to oceanographic research in China have been achieved. Based on numerical technologies developed in China, the opportunity to construct a global high-resolution ocean numerical forecasting system with higher resolution is nearing maturity.

From September 2016, a project entitled ‘Development of a Global High-resolution Marine Dynamic Environmental Forecasting System’ has been funded by ‘the Program on Marine Environmental Safety Guarantee’ of the National Key Research and...
Development Program of China. Based on publicly accessible data, this project will carry out supplementary observations and experiments; conduct further studies on multi-scale ocean mixing processes; improve the marine physical parameterization scheme; improve the numerical grid, algorithm technology, parallel technology, and coupling technology; and develop a combined global high-resolution ocean circulation model, wave–tide–flow coupling model, and tidal model for operational forecasting. This project will also develop a global high-resolution ocean wave forecast model, a pressure-coordinate ocean numerical model, a coupled ocean–atmosphere model, and other new technology from China’s own research and development for future operational applications. These models will be implemented to establish a global high-resolution ocean prediction system, and forecast products will be released, including temperature, salinity, velocity, and ocean wave and tidal currents with a horizontal resolution of 10 km. The accuracy of these products will reach an advanced international level. The system will clearly identify ocean mesoscale phenomena, with a forecasting validity time of five to seven days.

The project will enhance our theoretical understanding of upper-layer ocean mixing and internal mixing processes. A new generation of independent global operational oceanographic forecasting systems with a horizontal resolution of ~ 10 km (updated from ~ 25 km) will be established. The stable identification of ocean mesoscale phenomena has lifted China’s oceanographic forecast ability to a new level. It will provide more powerful scientific and technological support for the maintenance of national maritime rights, safe service in the ocean, marine disaster prevention and mitigation capabilities, and response to emergencies. This endeavor will implement the strategy aimed at strengthening China’s maritime power.

2. Research content

This project will accomplish its objectives through basic theoretical research, model development and expansion, and system establishment and application. For the theoretical research, further studies and detailed analysis of air–sea interface flux and multi-scale ocean mixing processes will be accomplished by in-situ observations in the South China Sea and laboratory experiments. The results will be used to optimize and improve marine hybrid-scheme parameters.

The numerical methods utilized by the model will be improved so that the global ocean circulation models developed by China’s own scientists (LICOM, LASG/IAP Climate System Ocean Model; Liu et al. 2012, 2004a, 2004b) and the wave–tide–flow coupling model (First Institute of Oceanography Coupled Numerical Ocean Model (FIOCOM); Qiao et al. 2010) can be implemented as operational forecasting systems. We will also develop a global wave model and a tidal model with full tidal forcing and celestial movement for operational application in the next four to five years.

To allow for innovative future applications, we will develop a pressure-coordinate ocean model with inherent energy conservation. Air–sea coupling forecasting technology will be advanced to develop a seamless forecasting system.

For system establishment and application, a global high-resolution ocean forecasting system will be developed and operated by the NMEFC to forecast waves, tides, temperature, salinity, and currents. Operational work flow, validation and calibration, and product release and integrated applications will be improved. Forecasting products for mesoscale ocean processes will be generated, including information on vortices and fronts. The key issues upon which the project will focus are outlined in the following subsections.

2.1. How can we understand ocean mixing mechanisms and improve mixing parameterizations for the upper and interior ocean?

The study of upper-ocean mixing processes and their parameterization is one of the key scientific issues that affect the performance of ocean models (Thorpe 1995; Garrett 1996; Cai and Gan 2001; Dai, Qiao, and Yuan 2007; Dai et al. 2010; Zhang, Cao, and Zhu 2011). The project will focus on the thermal and dynamical phenomena occurring in the surface and upper ocean; discuss the energy cascade and dissipation mechanisms; conduct research on wave breaking, wave–turbulence interaction, wind-induced near-inertial oscillations, ocean frontal instability, and other physical processes; clarify the roles of mass, momentum, energy, and other exchange processes; improve the mixing parameterization scheme of the upper ocean; and use the results of multi-functional flume experiments and off-sea science experiments to evaluate and verify parameterizations.

Experimental schemes generally include a lab sink, frontal survey along the continental shelf, and a subsurface buoy system. An experiment will be conducted in a wind–wave–current flume using PIV (particle imaging velocimetry) technology, ADV (acoustic Doppler velocimetry) technology, and LDV (laser Doppler velocimetry) technology to produce high-precision, high-frequency measurements of the velocity field that will be used to
validate mixing parameterizations of waves and breaking processes. Long-term, high-frequency platform observations of the ocean and atmosphere at Lufeng in the South China Sea (tropical deep sea), Bohe (tropical shallow sea), and Dong’ou (subtropical shallow sea) and in situ data (e.g. skin temperature, waves, profiles of temperature and salinity, and ocean current profiles) will be used to evaluate parameterizations of mixing processes driven by variability in the wave field and diurnal temperature fluctuations.

In the frontal area of the Qiongdong Shelf in Hainan Province, four cruises will be conducted in spring, summer, autumn, and winter, 2018–2019. Wind speed, ocean temperature, salinity, velocity, microstructure profiles of turbulent shear and temperature, nutrients, and chlorophyll will be measured at each station. A subsurface buoy system will be used for experimental verification of wind-induced near-inertial hybrid schemes, with plans to select two to three typhoon processes and arrange three sets of subsurface buoys and three sets of bottom observation systems.

Global high-resolution ocean models often exhibit significant differences when simulating mesoscale flows, due to the inadequate representation of horizontal mixing processes (Lellouche et al. 2013, 2015). Therefore, this project will compare parameterizations used in different models, verification and analysis of high-resolution observation data, energy exchange processes of multi-scale turbulent flows, and parameterizations that include the effects of turbulent mixing on horizontal momentum, and temperature and salinity. We will seek to understand and explain the mechanisms that contribute to horizontal momentum and the turbulent mixing of temperature and salinity.

In the stratified ocean, density perturbations can produce periodic internal tides, random near-inertial internal waves, and other small-scale mixing phenomena (Webband and Sugino; Gerkm and Shrira 2005). Mesoscale and sub-scale motions directly affect ocean mixing (Fan 2002; Liu and Fan 2005). Therefore, this project will study the generation, propagation, and dissipation mechanisms of global internal tides, the regional distribution of energy dissipation, nonlinear wave–wave interactions, large-scale interaction between currents and topography, the contribution of large-scale geostrophic adjustment to near-inertial internal-wave energy generation, the difference between the mixed layer and pycnocline depth inside and outside vortex zones, and quantify the influence of ocean eddies on vertical mixing.

The governing energy equation and mixing processes that occur during the propagation of internal tides will be studied by applying spectral analysis and other methods to historical temperature, salinity, and current data, satellite remote sensing observations, and climatological data from in-situ mooring and shipboard observations. Buoy trajectory data will be used to analyze the difference between vortex and non-vortex regions to quantify the influence of ocean vortices on vertical mixing. An internal wave parameterization will be developed, validated, and applied to research, based on global temperature and salinity profiles with high temporal and spatial coverage from fixed offshore platforms, submarine arrays, and other observational assets.

2.2. Developing a series of marine dynamic environment forecasting models based on pre-existing models using established technology

Operational oceanographic forecasting models are generally produced by developed countries in Europe and North America (Fujii and Kamachi 2003; Zheng et al. 2008). Such models play a central role in climate research and contribute to operational oceanographic forecasting (Liu et al. 2004a; 2004b). The proposed project will develop high-resolution, tripolar grid technology based on the full LICOM model algorithm, improve horizontal and vertical parameterization schemes, and develop online diagnostic techniques to establish a global high-resolution operational forecasting system with a horizontal resolution of 10 km.

We will investigate the influence of wind, waves, and tides on vertical mixing. The vertical mixing parameterization will be improved and optimized in regions with complex bottom topography to improve the performance of the model in marginal seas. In addition, we will compare and analyze different models (Crosnier and Le Provost 2007). These results will be (1) compared with the high-resolution observations used to validate and analyze mesoscale motions with large-scale and small-scale turbulent energy exchange processes; (2) used to analyze spectral characteristics of physical variables; (3) employed to improve and optimize the level of momentum and heat and salt; and (4) used to evaluate turbulent mixing parameterizations for ocean dynamics.

The common ocean mixing parameterizations are based mainly on work conducted during the 1980s and 1990s (Kitaigorodskii et al. 1983; Ezer 2000). These parameterizations describe large-scale shear processes adequately, but neglect interactions between waves, tides, and currents, which are important for ocean mixing (Qiao et al. 2004, 2010; Sun, Song, and Guan 2005; Veron, Melville, and Lenain 2009; Huang et al. 2011). This project will explore the mixing processes of mesoscale and small-scale ocean flows by combining scientific
experiments with theoretical analysis, investigating the contribution of waves and tides to ocean mixing, and developing an ocean mixing parameterization. We will evaluate multi-scale mixing parameterizations; analyze dependencies between the multi-scale mixing parameterizations and variables in the numerical model, input and output, and algorithm model design; perform model testing and debugging to analyze various combinations of mixing parameterizations and numerical models; analyze data and physical process diagnostics; and complete the evaluation of ocean multi-scale mixing parameterization. A new multi-scale coupled ocean model will be adopted to establish wave–tidal–current coupling by using the mixing parameterization for the upper and interior ocean. We will design the operational flow of data assimilation and the numerical model, fault tolerance mechanisms, and data backup and storage classification mechanisms, along with developing the diagnostic mode for experimental data and analyzing diagnostic data in real time.

2.3. Development of new independent ocean models with distinctive features

Establishing a numerical ocean model that conserves mass and energy, with actual energy inputs and transformations into conditional constraints parametric schemes, is an important way to reduce uncertainty in numerical models and improve numerical modeling capabilities (Zhang and Liang 1989; Zhang et al. 1996; Huang 1999; Jin, Zhang, and Zhou 1999; Huang, Jin, and Zhang 2001; Zhang, Lin, and Huang 2014b). Therefore, we will use a pressure-coordinate, energy-conserving ocean model (Zhang et al. 2014a; Ou et al. 2016) to study the influence of external mechanical energy on turbulent vertical mixing in the ocean, clarify the mechanisms of energy input into ocean processes, establish a turbulent flow parametric solution based on ocean wave and tidal energy inputs, and improve parallel computing capabilities. Finally, we will develop a new numerical ocean circulation model based on vertical pressure coordinates.

Using the existing PCOM (Pressure Coordinates Ocean Model; Huang, Jin, and Zhang 2001), we will extend the horizontal grid to the global scale and adapt and optimize the program modules, such as input/output and ocean power processes, to the new three-dimensional coordinate system. Based on methods for analyzing turbulent mixing resulting from waves and tides (Baumert, Simpson, and Sunderman 2005; Simmons et al. 2003), combined with observations and reanalysis of waves, tides, temperature, salinity, and currents, we will adjust and optimize model parameters and schemes to the new vertical pressure coordinates and associated numerical requirements. Based on the characteristics of the spherical multiple-cell (SMC) grid, a new and efficient parallel computing solution will be constructed to optimize multi-process parallel load balancing. Fortran-C mixed programming will be used in the heavy computing module to utilize graphics processing unit acceleration and further improve model performance.

To conduct numerical experiments of climatological states and numerical hindcast experiments of weather scales, we have developed a multi-resolution numerical ocean model with more than 50 vertical levels. The horizontal model resolution is 1/4° for global simulations and 1/16° for regional simulations. The tidal forcing along open boundaries was obtained from global ocean tidal models from the United States, Europe, and Japan, with horizontal resolutions of 8–50 km. We currently lack an independent global tidal model in China for operational forecasting. Therefore, the project will use the laws of motion for the Sun, Moon, and Earth, along with the law of universal gravitation, to generate the tidal forces of the Sun and Moon on the ocean, introduce tidal currents into the three-dimensional governing equations, and obtain the equations for global tides. Using a high-precision, high-resolution difference scheme, an independent global tidal current forecasting model will be established (Khatiwala 2003).

The Navier–Stokes equations are formulated for an inertial coordinate system, which take into account the translational motion of the Earth around the Sun and Moon, and the non-inertial effects of precession and nutation around the ecliptic pole (Wang and Wu 2013). Based on these assumptions, the three-dimensional governing equations for fluid flow, which include Coriolis terms and other non-inertial effects, are derived. The tidal forces of the Sun and Moon are added to the three-dimensional governing equations based on celestial movement; therefore, a global three-dimensional tide-wave dynamic equation based on celestial motions can be established. In regions with shallow topography, such as coastal seas, tides are often deformed by strong nonlinear effects. Therefore, we will develop a generation method for an unstructured, adaptive triangle-mesh grid with automatic adjustment of grid density, along with a corresponding numerical discretization scheme. The format design ideas of high-precision, high-resolution finite-volume Weighted Essentially Non-Oscillatory (WENO; Liu, Osher, and Chan 1994) and numerical dispersion of equations will be studied. According to the WAHR (Desai and Wahr 1999) model, a spheroidal model for calculating the theoretical value of the solid tide is
established. The solid tide level is computed using the formula for calculating the theoretical value of the solid tide. The global tidal model is used for parametric improvement and verification of the tidal height and the load stress on the spherical surface. By analyzing and comparing high-resolution regional simulation experiments, the effects of horizontal mixing parameterizations and bottom friction parameterizations on the model results will be studied. Considering recent research results, the optimal horizontal hybrid parameterization and bottom friction parameterization will be selected.

2.4. Integration and application of the global high-resolution marine dynamic environmental forecasting system for the primary goal of transforming the project results into real forecasting support

Application of the forecasting system is necessary to translate numerical forecasting models and technology into services for the marine economy and associated activities. The project will develop a data management system and integrated monitoring software for the different models based on the features of the high-resolution forecasting system. Based on the demand for identification of mesoscale eddies, the project will produce a global visualization system for high-resolution marine dynamic environment forecasting products to visualize currents, waves, tides, and other products. Dynamic displays and basic spatial query analysis will be used to provide efficient and easy-to-use products and services for users.

A data management system will be developed to include in-situ ocean data, basic geographic information, and a database of numerical forecasts. In addition, we will compile the global ocean environmental forecasting models developed by other research tasks. By using the platform of the National Oceanic Environment Forecasting Center or another designated computing environment, the optimization mode compilation and operation plan will be designed, the load balance of computing resources will be optimized, and the standardized data interface will be connected to the numerical products. The standards for statistical interpolation and interpretation technology will be established together with information services products.

We will conduct research on the international marine environmental prediction validation standards (Shen and Zuo 2006; Xie, Zhu, and Li 2008; Hernandez et al. 2009; Wang et al. 2010; Martin 2011; Rose, Roth, and Smith 2009; Oke et al. 2013; Ryan et al. 2015; Hernandez et al. 2015) to improve China’s operational evaluation methods and algorithms. We will develop an integrated monitoring system for data processing, model operation, post-processing, and distribution of data products and other operational processes, and establish an integrated monitoring system with multi-source data collection and integrated forecasting of various products and various business operation processes. We will develop a global visual system of ocean dynamic environment prediction to visualize ocean data, basic geographic information and numerical forecast products, and provide a unified platform for the production, analysis, and display of numerical forecast products. The global marine dynamic environment prediction products will be conducted using buoy data from ocean stations and supplementary observational data. Product development and verification of the military activities area and the forecasting factor will be carried out according to military requirements.

3. Structure and leadership

Based on the above issues, the project has been separated into nine tasks: (1) development of a global high-resolution numerical ocean circulation forecasting system based on LICOM; (2) development of a numerical ocean circulation model based on pressure coordinates; (3) parameterization and experimental verification of upper-ocean mixing processes; (4) parameterization and experimental verification of ocean-interior mixing processes; (5) development of a global high-resolution numerical wave prediction system; (6) development of a global high-resolution numerical tidal prediction system; (7) development of a global ocean coupled wave–tide–current forecasting model; (8) research on air–sea coupling technology; and (9) integration and application of the global ocean dynamic environment forecasting system. The logical relationships among the various tasks are shown in Figure 1.

Project leadership will be organized by the National Marine Environmental Forecasting Center. The Ocean University of China and the Institute of Atmospheric Physics of the Chinese Academy of Sciences will contribute to the project, along with 18 other organizations and more than 100 scientists from fields such as oceanography, marine environments, and marine meteorology. They will work for more than four years to complete all the project’s research missions.

4. Recent results

Multi-source ocean observations (including those from ships, global telecommunications systems, AVHRR, Merged Global Daily Sea Surface Temperatures (MGDSST), Group for High Resolution Sea Surface
Temperature (GHRSSST), Sea Surface Temperature and Sea Ice analysis system (OSTIA), Argo buoys, satellite altimeters, public cruises, ADCP data, and other data), basic geographic information (including that from GEBCO (General Bathymetric Chart of the Oceans) data and shoreline data), and forecasting products and reanalysis data (including those from the World Ocean Atlas (WOA), Global Digital Environment Model (GDEM), SODA, Comprehensive Ocean–Atmosphere Data Set (CODAS), GFS, low-resolution ERA-Interim atmospheric high- and low-resolution atmospheric forcing fields, and NCEP FNL atmospheric high-frequency forcing fields) will be collected.

To transmit and share the various observational datasets, we have determined a transmission frequency and content format for each type of data, allowing for individual data backups, transfers, and classification management processes. According to the observational measurements used to classify the data, the system automatically initiates data analysis, processing, storage, and so on. It divides the workflow into two independent processes for data files and data element processing, followed by site matching, data analysis, factor processing, quality control, data storage, and other bulk processing flows.

In this project, the eddy-resolving model of LICOM3 has been set up with a horizontal resolution of 10 km. The dynamic core and sub-scale processes have been improved, including changing the coordinate system to a tripolar grid, incorporating tidal mixing processes, and upgrading the coupler. The test results are similar to those of other operational forecasting systems, in which the RMSE of SST against global drifter data is less than 0.6°C and the anomaly correlation is greater than 0.6 at forecast lead times from one to seven days.

Theoretical studies of vertical mixing parameterization have been conducted to diagnose the physical characteristics of vertical mixing by offline methods. Using research conducted on parallelization of the SMC grid, a high-load balancing SMC grid parallel division method has been developed.

The project also focuses on the transmission, conversion, and dissipation mechanisms of near-inertial oscillation energy in the upper ocean. Based on submerged-buoy data, the energy transmission characteristics and variability of wind-driven near-inertial oscillations have been studied. Based on intensive observations of ocean fronts, a parametric formula for vortex mixing has been proposed for the continental shelf/slope in the northern South China Sea. The mixing rate at the front of the Qiongdong continental shelf during summer was fitted using the above parameterization. Based on ROMS, a high-resolution numerical internal tide model has been established, covering the South China Sea and the western Pacific Ocean. The processes of energy transmission and dissipation of the internal tide in the South China Sea have been studied, and the energy transmission processes in the northeast sea area of Taiwan and the western Pacific simulated.

Based on a concomitant assimilation method, an
estimation method for computing the viscosity coefficient profile of eddies in the Ekman boundary layer at the seafloor has been proposed. Based on observational data from submerged buoys, the stable and unstable features and the temporal and spatial variations in the internal tide north of the South China Sea have been discussed. The motion, intensity, and SST of mesoscale eddies (including cyclonic and anticyclonic eddies) were simulated by ROMS, with forcing from various wind fields and coupling mechanisms.

The project has already completed wave-breaking experiments for deep water based on linear focusing theory, and analyzed the mechanisms of wave energy transfer, along with characterizing wave variability during the transmission process. Based on the above dissipation and features, the source terms for energy dissipation associated with whitecaps in wave models caused by wave breaking have been improved, and the simulation accuracy for typhoon waves enhanced.

Using theoretical analysis and numerical hindcasts, a parameterization of the theoretical sea–ice–wave model based on WaveWatch III has been provided. From the governing equations of motion, the global hydrodynamic tidal equations for integrated tide-generating forces have been derived. A study on the WENO algorithm and adaptive grid is currently in progress. A global tide model, considering both the solid tide and load tide, has been established based on Finite-Volume Coastal Ocean Model (FVCOM), with the simulation showing reliable results, especially in terms of agreement between the simulated results and observations at the amphidromic point for the M2 partial tide.

A coupled global numerical wave–tide–circulation model (FIOCOM) with a horizontal resolution of 0.1° has been developed. Based on satellite altimeter data (AVISO) and Argo buoy data, vertical mixing caused by mesoscale eddies in the Kuroshio Extension has been studied using a synthetic analysis method. Based on a comprehensive review of advanced coupler technology, a flexible coupling system framework, a detailed coupling process, and an efficient operating mode have been designed and implemented on the supercomputer platform at Tsinghua University.

Considering the operational and application requirements for global operational oceanographic forecasts, a unified data standard and database storage structure have been designed with reference to international standards, and stable and efficient functional modules developed for data acquisition, processing, quality control, retrieval, analysis, and management. A preliminarily standardized assessment module for operational numerical forecasts has been developed (Ling, Wan, and Liu 2017).

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