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Short communication

Software development of the TaIwan Multi-scale Community Ocean Model (TIMCOM)

Chih-Chieh Young[a], Yu-Heng Tseng[a,b,*], Mao-Lin Shen[a], Yu-Chiao Liang[a], Mu-Hua Chen[a], Chia-Hung Chien[c]

[a] Department of Atmospheric Sciences, National Taiwan University, Taipei 10617, Taiwan
[b] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO, USA
[c] ARAVision Incorporated, New Taipei 23141, Taiwan

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ABSTRACT

The recently developed TaIwan Multi-scale Community Ocean Model (referred as TIMCOM), evolving from the DieCAST (Dietrich Center for Air Sea Technology) model, provides an accurate, efficient, and user-friendly framework to study a broad spectrum of oceanic flows, ranging from bays and coastal to global oceans. The model employs the finite volume concept and discretizes the primitive equations using the modified leapfrog scheme and fourth-order spatial approximation. The pressure Poisson equation is efficiently solved by the error vector propagation (EVP) method. Adaptive grid-coupling technique is further adopted to provide the required resolution for the targeted region without excessive computation. Besides, a user-friendly interface is introduced to simplify user customization. Two practical applications, global and dual-grid North Pacific Ocean modeling frameworks which are used to simulate the global and regional ocean-climate variability, clearly show the robustness, efficiency, and accuracy of the TIMCOM software.

Software availability

Name of the software: TIMCOM
Developers: C. C. Young, Y. H. Tseng, M. L. Shen, Y. C. Liang, M. H. Chien, C. H. Chien
Contact address: Department of Atmospheric Sciences, National Taiwan University, Taipei 10617, Taiwan
Hardware requirements: PC (UNIX, Mac or Windows system)
Software requirements: any fortran 90 compiler and NetCDF library
Availability and cost: A copy of the source code can be freely downloaded from http://efdl.as.ntu.edu.tw/research/timcom/index.html.

1. Introduction

Ocean circulation (consisting of surface and underlying currents) plays an important role in the marine ecosystem and the global climate variability (Gill, 1982). It is an integrated system driven mainly by the wind forcing and density gradients attributed to thermohaline differences. Through their transports in ocean currents, the redistribution of geochemical species, solar energy and absolute angular momentum regulates the balance of global marine and climate systems. Over the last century, the general pattern of ocean circulation has been altered in response to anthropogenic climate change/global warming (IPCC, 2007), threatening the earth environment and human life. This motivates better understanding of ocean circulation and its associated environmental consequences.

Three basic approaches can be used to study ocean circulation: (i) observations, (ii) theories, and (iii) numerical modeling (Nansen, 1902; Stommel, 1948; Bryan, 1969). Although observations from ships, floating buoys, or the satellite imaging techniques are essential for understanding the ocean, they can only provide a qualitative description due to the lack of long-term or sufficient subsurface data. Many theoretical studies have established the fundamental knowledge of ocean circulation (Colling, 2001). However, only little is known about the ocean interior, especially its dense deep currents. For example, recent observation (Bower et al., 2009; Day, 2009) challenged the traditional thinking about the Gulf Stream (GS), its coupling to underlying dense currents, transient eddies, and the associated climatologically important thermohaline circulation (forced by wind induced vertical mixing, surface heating/cooling and freshwater sources/sinks). In addition, the

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* Corresponding author. Present address: CGD/NCAR, 1850 Table Mesa Dr., Boulder, CO 80305, USA. Tel.: +886 2 33663918.
E-mail address: yhtseng@as.ntu.edu.tw (Y.-H. Tseng).

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subsurface equatorial ocean dynamics is not fully understood, such as the role of nonhydrostatic vertical mixing that is coupled to the thermohaline circulation and equatorial wind forcing. All of the above require the third approach, i.e. numerical modeling, to verify the detailed feedback and even project the future climate state in terms of the completed representation of the three-dimensional global ocean circulation (Semtner, 1995).

Being the primary tool for ocean climate studies, efficient and accurate simulation of global ocean circulation is still demanding and challenging. Continuous ocean modeling has been attempted and progressed for a few decades to develop unified models that can effectively resolve multi-scale spatial and temporal oceanic processes (Griffies et al., 2005). One can refer to the articles by McWilliams (1996) and Griffies et al. (2000) for thorough reviews of recent developments. DieCAST (Dietrich Center for Air Sea Technology; see Dietrich and Ko, 1994) is a robust and accurate oceanic general circulation model among many others. It solves primitive equations using a fourth-order central difference approximation on a mixed collocated and staggered grid to minimize the numerical errors. The resulting pressure Poisson equation can be efficiently solved by the error vector propagation (EVP) method (Madala, 1978; Roache, 1995) with an operation count of $O(n^{3/2})$, where n is the total number of horizontal grid points. Advanced grid coupling technique also provides an adequate grid arrangement to resolve the fine-scale features in detail and reduce the overall computation expense (Dietrich et al., 2004b, 2008). Previous works indicated that DieCAST can predict more realistic results at a faster computing time for several benchmark tests (e.g., Dietrich et al., 1987; Tseng and Dietrich, 2006) and has been successfully used in various applications (e.g. Dietrich and Ko, 1994; Dietrich, 1997; Tseng et al., 2005). Also, Canadian DieCAST (CANDIE; Sheng et al., 1998; Lu et al., 2001) has been developed and expanded to a nested-grid ocean modeling system for free-surface coastal water studies (Zhai et al., 2008). Despite its outstanding accuracy, efficiency, and applicability (comparable or competitive to those in several existing ocean models), DieCAST was not commonly used in the ocean community due to many reasons.

The major goal in this study is to develop a powerful and user-friendly TaIwan Multi-scale Community Ocean Model (TIMCOM) to study a broad spectrum of ocean flows. Evolving from the DieCAST model, TIMCOM not only shares the same robust numerical features but also involves some improvement/extension. Particularly, the software is completely redesigned and written in the modular fashion using Fortran 90. All interested users can easily modify the existing configurations and apply to any specific ocean basin they are interested in. We believe that TIMCOM can further serve as a key component in an earth system model for future global/regional ocean-climate application.

2. Description of TIMCOM

2.1. Mathematical formulation and numerical methods

TIMCOM solves the three-dimensional (3D) primitive equations using Boussinesq and hydrostatic approximations for an incompressible, stratified fluid in the spherical (or Cartesian) coordinate. Rigid-lid approximation at the top boundary is generally appropriate for the applications of slow-mode ocean circulations (Tseng et al., 2005). For the studies of fast-mode coastal surface motions, e.g. tides, or strong flows over rapidly-changed sloping bathymetry associated with considerable vertical acceleration, hydrostatic free-surface (Lu et al., 2001) and non-hydrostatic features (Dietrich & Lin, 2002; Tseng et al., 2005) have been respectively incorporated into TIMCOM. Currently, both rigid-lid and free-surface options are available in the public domain. The enhanced non-hydrostatic version is available under license agreement considering the ongoing progress of model development and practical research.

TIMCOM uses the fourth-order spatial approximation with the modified leapfrog teme-stepping scheme (see Sanderson and Brassington, 1998; Williams, 2009) on a mixed collocated and staggered grid (i.e. a blend of Arakawa A and C grids). Particularly, the modified leapfrog time-stepping method can provide third-order accuracy in amplitude (Williams, 2009), superior to that in the traditional filtering approach (Asselin, 1972) or filtered leapfrog-trapezoidal scheme (Dietrich, 1975; Dietrich et al., 1975). The two-step predictor-corrector procedure (Zang et al., 1994) in the overall numerical algorithms will be briefly presented in the following. For more details, one can refer to TIMCOM's user manual (Young et al., 2011).

(1) Predictor step: To obtain the intermediate velocities, momentum equations are discretized at the cell centers (i.e. the collocated grid) using centered time-stepping (modified leapfrog) for advection and fourth-order pressure gradient, and forward time-stepping for diffusion. The sea water density is calculated by an accurate and efficient density calculation that includes pressure effects and fits to the full UNESCO equation of state (Sanderson et al., 2002). Note that pressure is expressed in terms of forward barotropic surface pressure and centered baroclinic pressure. Vertical viscosity is parameterized by a modified Richardson-number based approach of Pacanowski and Philander (1981), which can provide a reasonable representation in simulating tropical circulation. Comparison and discussion of vertical-mixing schemes can be found in the literature, e.g. Li et al. (2001) or Durski et al. (2004). Alternate formulations, e.g. high-order turbulence closure scheme of level 2.5 (Mellor and Yamada, 1982) or K-Profile Parameterization/KPP (Large et al., 1994), can be applied later by the users for a variety of realistic setting. Coriolis terms are further updated through a trapezoidal treatment. The predicted A-grid velocities are then interpolated to the cell faces (i.e. staggered locations) using the fourth-order control volume formula (Sanderson and Brassington, 1998). Similar procedure is applied to the conservation equations for final potential temperature and salinity.

(2) Corrector step: Forward surface pressure used in the predictor step requires further correction, i.e. centered time-stepping, to achieve the final flow fields. Surface pressure corrections and corresponding C-grid velocity adjustments can be obtained by imposing the vertically integrated continuity equation (i.e. divergence free at each control volume) and solving the resulting Poisson equation using the efficient error vector propagation (EVP) method (Madala, 1978; Roache, 1995). The A-grid velocity increments are calculated using a reduced numerical dispersion approach in which the changes of C-grid velocity are interpolated with fourth order accuracy to the A-grid. Once surface pressures and horizontal velocities are fully updated, vertical velocity is diagnostically determined by the continuity equation. Note that TIMCOM adopts a modified leapfrog formula in time (Williams, 2009). Compared with the standard Asselin filter used in DieCAST, this modification improves the time truncation error in amplitude from first-order to third-order accuracy; first-order accuracy is adequate for most applications if a small time step is applied, but third-order method of Williams (2009) may be significantly better for forecast applications using a larger time-step. The effects of the modified leapfrog formula on the global ocean circulation modeling are investigated and the results will be reported in Young et al. (in preparation) separately.

TIMCOM also provides a multiple-grid modeling flexibility (e.g. Dietrich et al., 2004b; Tseng et al., in press) to better represent the complicated geometry (topography) near the coast using a finer grid or reduce the unnecessary computational costs in some practical applications. As a result, the required accuracy in the targeted domain can be achieved efficiently. Indeed, Dietrich et al. (2008) used six two-way-coupled grids to efficiently and accurately simulate the full Mediterranean Sea and North Atlantic ocean circulation, including the realistic exchange of Mediterranean and North Atlantic water through Strait of Gibraltar and the Mediterranean Overflow Water, notably running on a personal computer; this would have extremely demanding and had never been done previously. The simple but strategic two-way coupling can ensure precise flux conservation, stability and efficiency at the same time. One can refer to Tseng et al. (in press) for details.

2.2. *Software development and program structure*

TIMCOM is developed to provide flexible and robust ocean modeling software for the ocean community while retaining the advantage of numerical accuracy and efficiency in DieCAST. Major advancements are briefly summarized as follows. New Fortran 90 format written in a modular fashion (rather than Fortran 77 used in DieCAST) avoids confusion/repetition and makes future programming extension/modularization easy. Free surface option, multiple-grid flexibility, an accurate density calculation and a new time-stepping scheme further enhance its numerical capability. The addition of Lagrangian particle tracking and scalar transport functions help the study of pollutant transport driven by the physical oceanic processes. Most important of all, a user-friendly interface (i.e. Fortran namelist and preprocessing scripts) is introduced to simplify user customization. The Network Common Data Form (NetCDF) is adopted for the model standard outputs, allowing synthesis of data creation, access, operation, and sharing.

For program structure, TIMCOM software system contains three components: (i) Preprocessor, (ii) Main Code, and (iii) Postprocessor (see Fig. 1). The Preprocessor prepares required information for the computational domain(s), initial and boundary conditions. It generates customized grid coordinate and creates bottom topography (e.g. interpolated Etopo5 bathymetry data), initializes temperature and salinity fields (e.g. climatology data of Levitus and Boyer (1994)), and imposes boundary condition or forcing (e.g. surface wind stress from monthly data of Hellerman and Rosenstein (1983)). The Preprocessor also calculates the influence matrix and its inverse for the EVP elliptic pressure solver.

The Main Code just solves the ocean circulation patterns numerically. Notice that multiple-domain cases need the grid-coupling block setting for data transferring and communication. New auxiliary functions, e.g. Lagrangian particle tracking or scalar transport equation, can be turn-on/off based on different research purposes. The model results are written into the NetCDF format files. Finally, both MATLAB and NCL scripts are provided in the Postprocessor for better and easy visualization.

3. Model applications

Several benchmark tests and applications have been used to examine and validate the capability of TIMCOM. Here, we illustrate two standard configurations and show the accuracy, efficiency, and benefits of the grid-coupling framework in TIMCOM software: (i) 2° global ocean modeling; and (ii) dual-grid North Pacific Ocean modeling. A brief description is given below. Detailed tutorials for both cases are available in the user's manual (Young et al., 2011) and are not included for brevity.

The first global model application covers the entire globe domain from 72°S to 72°N with a closed northern boundary slowly nudging toward climatology in a sponge layer. The simulation is carried out on a 2° Mercator grid and 25 linear-exponentially stretched vertical layers. The time increment Δt is 450 s. The

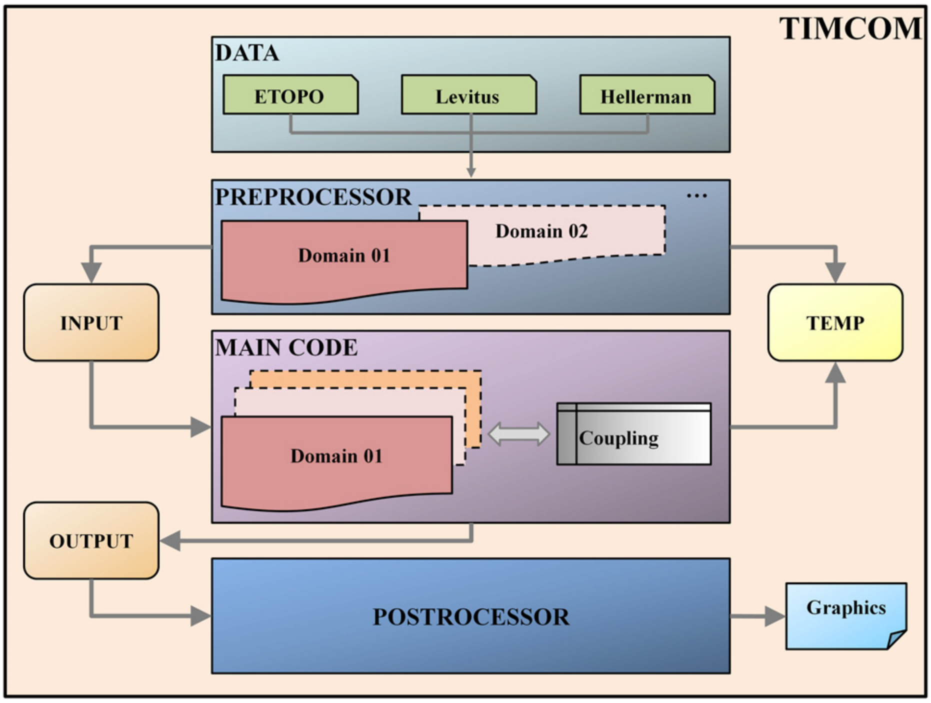

Fig. 1. Program structure of the TIMCOM software system.

depth is derived from the ETOPO5 bathymetry data. Initial potential temperature and salinity fields are specified using climatology of Levitus and Boyer (1994). Density (a function of potential temperature, salinity, and pressure) is then determined by the full UNESCO equation of state (Sanderson et al., 2002). The surface forcing is imposed by the monthly climatological winds of Hellerman and Rosenstein (1983). Note that surface sources of heat and freshwater are specified by a non-damping approach of Dietrich et al. (2004a). Fig. 2 shows the yearly averaged sea surface height (SSH), temperature (SST), and upper 50 m velocity at the 30th modeled year. Most important current systems are reasonably developed in a quasi-steady sense. More detailed discussion and the validation of even higher resolution (i.e. 1/4°) results based on the parallel version of TIMCOM can be found in the work of Tseng and Chien (2011).

The second application zooms in to the high-resolution simulation of the western boundary current, Kuroshio, in the North Pacific Ocean framework, which has drawn great research interest due to its significant influences on ship navigation, fisheries, marine resources, and global/regional ocean climate variations (Tseng et al., in press). Based on the dual-grid framework in the TIMCOM software, the whole North Pacific Ocean (from 100°E to 80°W and from 30°S to 60°N) is divided into two domains, the North Pacific Basin domain (NPB, east of 150°E) and TAIwan regional domain (TAI, west of 150°E), respectively. The TAI (or NPB) domain is discretized with a 1/8° (or 1/4°) Mercator grid and 25 linear-exponentially stretched vertical layers. The time increment used for simulation is 200 s (or 600 s). The lateral boundaries are all closed except that the southern boundary of the NPB domain is slowly nudged toward climatology in a sponge layer. An equatorial sponge layer may also be useful because the observed strong stacked equatorial vortices may require non-hydrostatic processes to describe their completed dynamics. The lateral boundary exchanges are specified by the energy conservative two-way coupling algorithm (Dietrich et al., 2004b; Tseng et al., in press). Model initialization and surface wind forcing follow the same procedure described previously. Fig. 3(a) shows the yearly averaged model results of SSH and upper 40 m velocity in the TAI domain. It is clear that the Kuroshio is properly resolved. Major features of Kuroshio and its validations, e.g. volume transport, seasonal variability, and its path, have been carefully discussed by Tseng et al. (in press) and are skipped here. Fig. 3(b) shows an example of the Lagrangian trajectory of the particles released at southern Taiwan, demonstrating the influence of ocean currents on pollutant

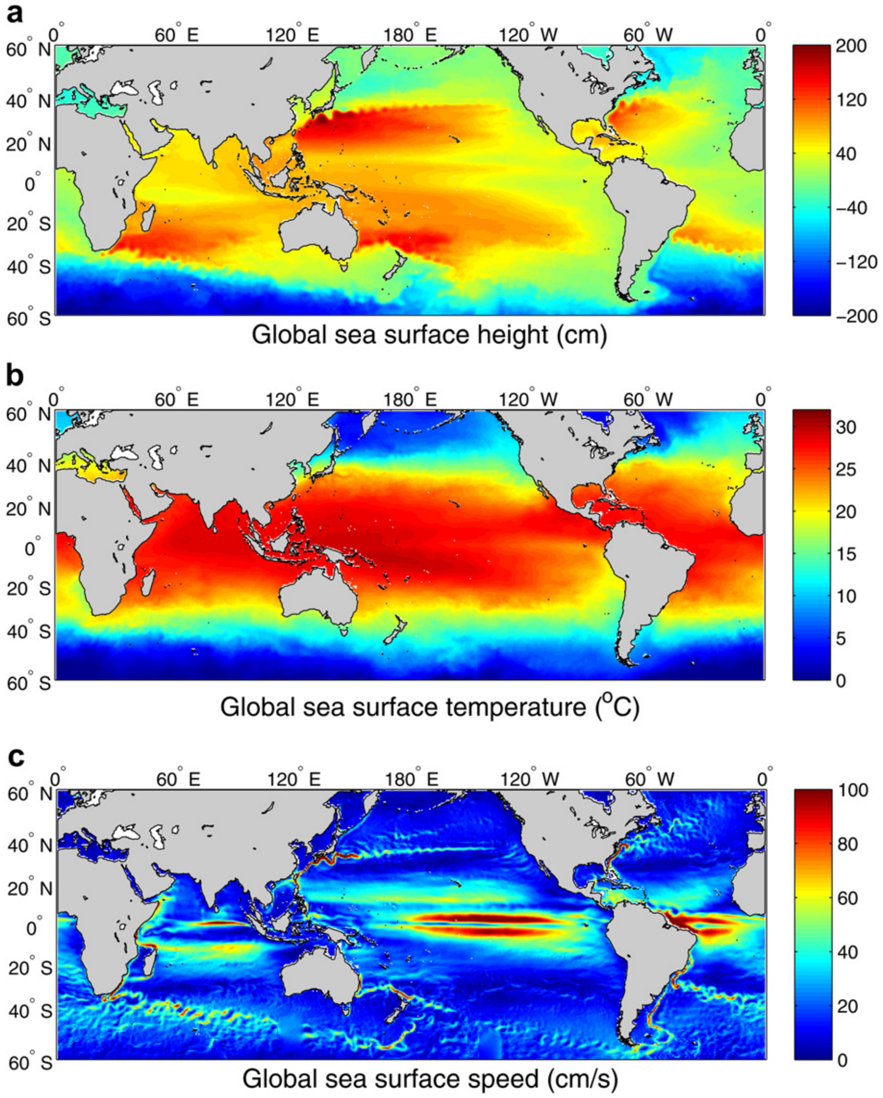

Fig. 2. Yearly averaged sea surface height (SSH), temperature (SST), and upper 50 m velocity at the 30th modeled year.

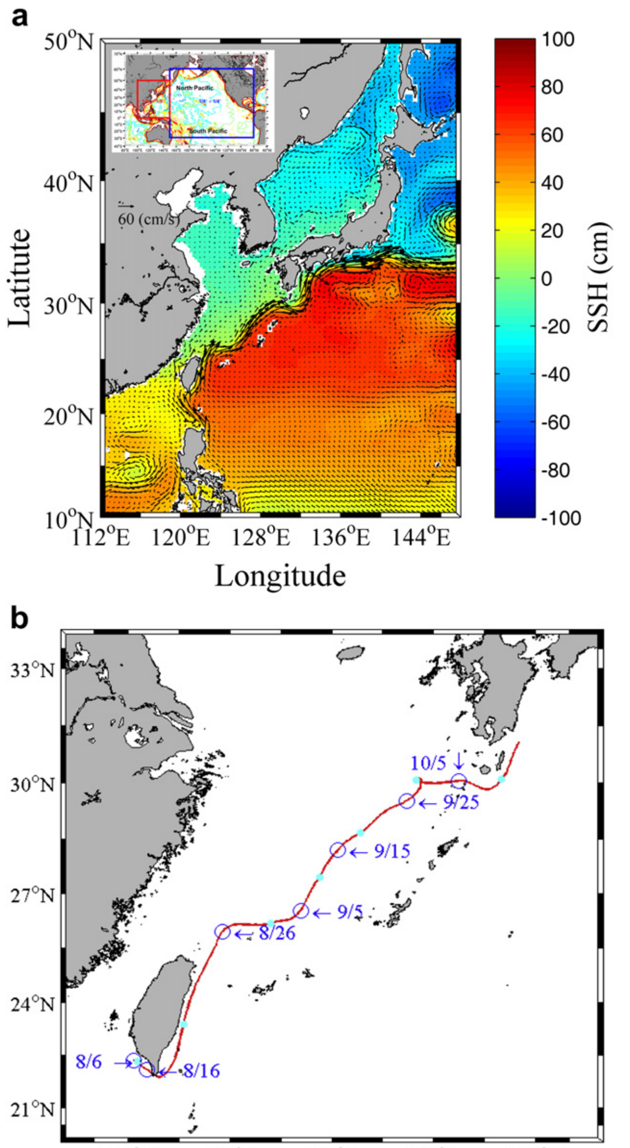

Fig. 3. (a) Yearly averaged sea surface height (SSH) and upper 40 m velocity in the TAI domain and (b) Lagrangian trajectory of the particle released at southern Taiwan.

transport. Here, we should emphasize that the multi-grid framework in the TIMCOM software facilitates high-resolution simulation of the targeted area with affordable computational cost.

4. Conclusions

The recently developed TIMCOM is a flexible and robust software package for simulating ocean general circulation. It solves the 3D primitive equations using the well-validated fourth-order accurate numerical method in the DieCAST ocean model (Dietrich and Ko, 1994; Dietrich, 1997) and the modified Leap-frog time stepping (Williams, 2009). Moreover, the grid coupling technique (Dietrich et al., 2004b; Tseng et al., in press) is employed for the applications with complicated geometry, allowing high resolution in the targeted area at minimum computational cost. The new capability of Lagrangian particle tracking and scalar transport enhances the understanding of pollutant transport under the influence of ocean circulation.

The TIMCOM software package consists of three components. The Preprocessor customizes the required input data. The Main Code simulates the detailed circulation patterns. The Postprocessor reads the standard NetCDF output and automatically creates graphic results. In contrast to the DieCAST ocean model, the TIMCOM software is organized and written in Fortran 90 using a modular fashion, giving higher programming convenience and maintenance efficiency. Moreover, a user-friendly interface simplifies user customization.

Finally, two standard model applications (global ocean modeling and dual-grid North Pacific Ocean modeling frameworks) have clearly shown the accuracy, efficiency, and benefits of multi-grid framework in TIMCOM. Both are the default configurations of the current software. The hydrostatic version of TIMCOM software (either rigid-lid or free-surface version) is now released and can be freely downloaded (http://efdl.as.ntu.edu.tw/research/timcom/index.html). Currently, some advanced model features such as (i) immersed boundary methods for topography, (ii) turbulence closure parameterization options, (iii) hindcast wind forcing capability, (iv) ensemble simulation capability, and (v) ocean biogeochemistry dynamics are still under development and will be reported in the near future.

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