Ocean Modelling with MOM

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The Modular Ocean Model (MOM) is a hydrostatic primitive equation numerical code of use for the scientific exploration of ocean dynamics covering a broad range of space and time scales. In this article, we present an overview of the MOM effort and discuss recent developments and applications.

A Community Model Code

Numerical ocean modelling at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) originates from Joe Smagorinsky's recruitment in 1962 of Kirk Bryan, then at Woods Hole. Smagorinsky envisioned a suite of numerical models for use in understanding mechanisms for weather and climate phenomena, and for dynamical forecasts. This pioneering vision is fundamental to numerical modelling of weather and climate today. With patient and commited leadership, solid funding, and persistent scientific and engineering efforts, the 1960s and 1970s saw Bryan, Mike Cox, and collaborators such as Bert Semtner, pioneering global ocean simulations (Bryan 1969b, Bryan et al 1975, Bryan and Lewis 1979)

Release of the ``Cox Code'' (Cox 1984) established a tradition whereby GFDL provides institutional support for the use of its ocean codes. These efforts have seeded many other ocean modelling initiatives, such as those at Southampton for studies of the Southern Ocean and global eddying simulations, as well as at the Hadley Centre in the context of global climate modelling. The development of MOM1 (Pacanowski et al 1991) furthered this influence by establishing the starting point for efforts at Los Alamos, Paris, Australia, NCAR, and elsewhere. It is difficult to garner robust statistics for free software. Nonetheless, the most recent release of MOM (version 4) has more than 500 registered users since early 2004, with users coming from dozens of countries, and many representing multiple collaborators. Hence, there are well over a thousand international scientists in the MOM4 community using the code for a huge variety of scientific investigations on nearly every conceivable computer platform.

Central to the success of MOM is the ease of setting up new experiments to meet the unique needs of each investigator. This ease arises from the distribution with MOM of various auxiliary codes aimed at developing the model grid, topography, initial conditions, and boundary conditions. MOM is also packaged with the GFDL Flexible Modeling Framework (FMS). Much of the engineering exercise of running ocean models relies on powerful, yet often complex, computers. FMS provides parallelization primitives to facilitate MOM's efficient use on both vector and scalar machines. FMS also contains a general framework for coupling to other component models, such as atmosphere and ice models. Indeed, two of the roughly ten test cases with MOM4 are coupled ocean-ice models. Additionally, MOM comes with an ocean biogeochemistry model that manages multiple tracers in a flexible manner. For diagnostics, MOM incorporates the FMS diagnostic manager whereby a table entry allows for the addition or removal of a diagnostic field at runtime. Hundreds, if not thousands, of variables are tagged for inclusion in this table, and additional variables are trivial to include.

Support for a community of users is fundamental to GFDL's commitment to MOM. The reasons are many, but include the exposure that algorithms get from a broad scientific community. This exposure assists in uncovering code bugs, formulational inconsistencies, and physical limitations. To assist in this exposure, MOM developers have consistently held model documentation a primary aspect of each code release (Cox 1984, Pacanowsk et al 1991, Pacanowski 1995, Pacanowski and Griffies 1999, Griffies et al 2004, Griffies 2004. 2007). Such documentation aims to inform the MOM community regarding the rationale of its algorithms, thus assisting in the intelligent and critical use of the code. A key feature of a community model is the contribution of dynamical methods, subgrid scale parameterizations, and diagnostics to the main code branch. Nearly 20 years of MOM experience illustrate how community contributions greatly enhance the code integrity and breadth of applications. Finally, a scientifically useful numerical tool is far more than code. It is also a repository of experience garnered by a broad range of applications and wide user base. Without such experience, knowledge of the code's abilities and limitations is absent, and its use as a scientific tool is handicapped.

Suite Of Algorithms

The Cox Code was based on the Boussinesq primitive equations posed on a finite difference B-grid using z-coordinates in the vertical and spherical coordinates in the horizontal. It used the Bryan (1969a) rigid lid to split the fast barotropic waves from the slower motions of primary interest. This framework proved sufficient for an amazing number of insightful ocean climate model applications. However, as our scientific understanding of the ocean evolves, so does our understanding of how to simulate the ocean, with limitations of the early algorithms readily being exposed as applications broaden and simulations are compared to the growing suite of observations. This evolution of understanding and application has motivated the continual evolution of MOM throughout the 1990s and 2000s.

The most recent version of MOM is known as MOM4p1 (Griffies 2007). This code provides options for a suite of vertical coordinates, with pressure and functions of pressure suitable for non-Boussinesq dynamics, thus rendering a more accurate representation of the ocean free surface due to an explicit inclusion of steric effects. It uses a split-explicit algorithm for the barotropic and baroclinic motions, following the method originally proposed by Killworth et al (1991) and slightly modified by Griffies et al (2001) and Griffies (2004). This approach allows MOM to explicitly represent tides; employ a realistic hydrological cycle, rather than parameterize its effects with unphysical salt fluxes (Huang 1993); to use realistic bottom topography without concerns for rigid lid instabilities (Killworth 1987); and to run efficiently on parallel computers without bottlenecks of global sums arising in elliptic methods (Griffies et al. 2001)

MOM4 represents the bottom topography using the partial steps of Adcroft et al. (1997) and Pacanowski and Gnanadesikan (1998). Partial steps more faithfully represent the ocean's bottom by allowing the thickness of a grid cell to be a function of horizontal and vertical position. The cell thicknesses can also be functions of time, as appropriate for non-geopotential vertical coordinates such as pressure. In the horizontal, MOM4 uses generalized orthogonal coordinates, thus allowing it to exploit a broad range of locally orthogonal grids, such as the tripolar grid of Murray (1996) now standard for GFDL ocean climate simulations (Griffies et al 2004).

Leap-frog time stepping for the inviscid dynamics, standard until MOM3, has been replaced by a staggered forward time stepping scheme (Griffies 2005, Griffies et al 2005). This method removes the leap-frog computational mode, and renders a numerically precise conservation of mass and tracer. In some configurations, it can update the ocean state using twice the time step as the leap-frog, thus halving model cost.

The goal of a tracer advection scheme is to minimize dispersion errors and false extrema, maintain strong fronts and gradients, and keep spurious levels of diffusion low. There is no perfect scheme available, with MOM4p1 providing ten schemes, each with their pros and cons. However, recent experience at GFDL has shown some compelling reason to consider the Prather (1986) scheme as a benchmark for one of the best available.

Ocean climate models have traditionally been at the coarser end of the model resolution spectrum due to the global domain and long integration time. Climate resolutions necessitate a suite of subgrid scale parameterizations. MOM4 provides a suite for mesoscale eddies (Gent et al 1995, Griffies et al 1998, Griffies 1998, Visbeck et al 1997); overflows (Beckmann and Doescher 1997, Campin and Goosse 1999); tidal mixing (Simmons et al. 2004, Lee et al. 2006); lateral friction (Griffies and Hallberg 2000, Large et al. 2001); and boundary layers (Pacanowski and Philander 1981, Large et al. 1994, Chen et al. 1994).

Recent developments with MOM4p1 have exposed the code to regional modelling applications that have prompted a revision of MOM's radiating open boundary conditions. Additionally, MOM4p1 provides a wrapper for the Generalized Ocean Turbulence Model (Unlauf et al. 2005), thus facilitating the use of a wide class of turbulence closures commonly applied to regional and coastal applications.

Ongoing Development

A key aim of future coupled climate modelling at GFDL is to produce ensembles of centennial-scale simulations with a mesoscale eddying ocean using GFDL's computer resources. For this purpose, we are prototyping a 1/4 degree configuration with 50 levels. This model runs on 800 SGI Altix processors with a turnaround of roughly 100 simulated years per calendar month.

Figure 1 (page 13) shows the zonal velocity at 400m from a preliminary simulation. Space does not allow for us to compare with other simulations. Nonetheless, we note that the simulation quality is comparable to that achieved at finer resolutions, such as that described in Richards et al. (2007). We conjecture that such quality arises from the generally small lateral friction available with the Smagorinsky biharmonic scheme (Griffies and Hallberg 2000), along with the strong tracer gradients maintained with Prather (1986) advection.

In addition to MOM development, GFDL ocean model developers have focused on merging features available in three ocean models: the Hallberg Isopycnal Model, the MITgcm, and MOM. This effort aims to remedy problems inherent in each model, to more rigorously test methods and parameterizations, and to optimize human resources. The resulting unified code is expected to mature during the upcoming years into a generalized vertical coordinate model with both regional and global applications.

Dedication

Throughout the history of ocean model development at GFDL, Peter Killworth has been an active participant in the community of users and developers. We sincerely thank Peter for his years of tireless service, through insightful model applications and analyses, novel algorithm designs, and super-human efforts as editor of the journal Ocean Modelling.

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A series of quasi-global eddy-resolving ocean simulations

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Introduction

Rapid increase of computer power and significant improvement of ocean general circulation models (OGCMs) with advanced parameterizations enable us to perform long-term simulations with global high-resolution OGCMs, which represent well not only the global circulation but also pathways of narrow strong currents such as western boundary currents, frontal structures, and small scale phenomena including mesoscale eddies. The recent advent of massive parallel computer systems, including the Earth Simulator (ES) with 40 Tflops peak performance established in 2002, has opened an era of global eddy-resolving ocean simulations. We have performed a series of quasi-global simulations on the ES with a horizontal resolution of 0.1° (see below). The simulations display oceanic mean fields and variability with rich fine-scale structures, which are comparable to available observations, and intriguing results are emerging from the realistically simulated oceanic fields. The present article introduces a few examples to illustrate the great opportunity the high-resolution ocean simulations can offer to advance our understanding of ocean circulation and its variability.

Model and simulation description

OFES (OGCM for the ES) is an OGCM parallelized and highly optimized for the ES, based on MOM3 (Pacanowski and Griffies, 1999). The horizontal resolution of our quasi-global eddy-resolving model, extending from 75°S to 75°N, is 0.1° and the number of vertical levels is 54. As our first attempt, a 50-year spin-up simulation was conducted forced by monthly climatological NCEP/NCAR reanalysis fields (Masumoto et al., 2004). Surface heat fluxes are calculated using bulk formulae, and the surface salinity flux is derived from reanalysis precipitation and estimated evaporation with an additional term restoring to the monthly climatology. Following this spin-up simulation, we have performed a hindcast simulation forced by daily NCEP/NCAR reanalysis fields for the period from 1950 to 2006 (NCEP hindcast simulation, Sasaki et al., 2007). Furthermore, an additional hindcast simulation driven by the QuikSCAT satellite wind stress, provided from the J-OFURO dataset (Kutsuwada, 1998; Kubota et al., 2002), has been performed (QSCAT hindcast simulation, Sasaki et al., 2006).

50-year spin-up simulation with monthly climatological forcing

Figure 1 (page 6) shows a snapshot of the simulated surface current in the spin-up simulation. Narrow strong currents including western boundary currents and equatorial current systems are well represented, and small scale features such as mesoscale eddies can be identified not only around the strong currents but also in interior basins. Flows through narrow passages near the marginal seas including the Indonesian archipelago, sharp frontal structures accompanying narrow currents in the Kuroshio Extension regions and the Antarctic Circumpolar Current, and separations of western boundary currents are among many examples realistically represented in the spin-up simulation. Variation of the simulated sea surface height (SSH) is also comparable to satellite observation (Masumoto et al., 2004). In the mean fields, coherent vertical structures of alternating zonal jets in the world ocean are confirmed by the OFES results, and the coupling between the jets and mesoscale eddies is implied (Maximenko et al., 2005). These successful representations in the spin-up simulation encourage us to proceed to the subsequent hindcast simulation. It is noted that the spin-up simulation has been extended up to 98-years long, incorporating chlorofluorocarbon tracers (Sasai et al., 2004).

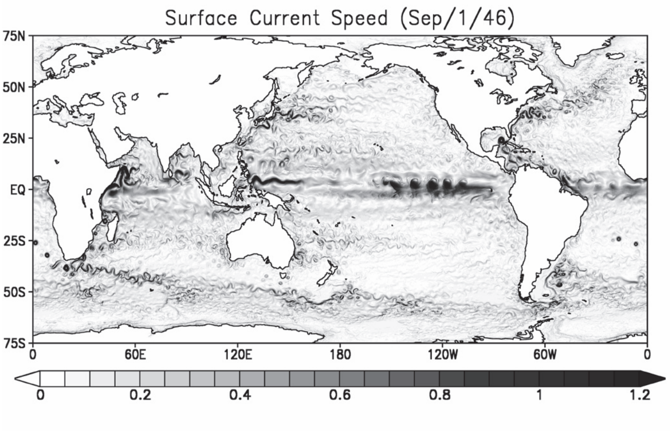

Figure 1. Snapshot of simulated surface current speed (m sec-1) based on the OFES spin-up simulation

Multi-decadal hindcast simulation with NCEP reanalysis forcing

The NCEP hindcast simulation provides a long-term dataset useful to study intraseasonal to decadal variations in realistic oceanic fields. The simulated fields capture many observed features of large-scale oceanic variations on interannual to decadal time-scale such as El Niño, Indian Ocean Dipole events, Pacific Decadal Oscillation (PDO), and Pan-Atlantic Decadal Oscillation, as well as intraseasonal variations in the equatorial Pacific and Indian Oceans (Sasaki et al., 2007). Furthermore, the multi-decadal integration of the eddy-resolving model provides an unprecedented opportunity to study the low-frequency variability of narrow oceanic jets.

A remarkable example, in this regard, is a series of studies of decadal variation of the Kuroshio Extension (KE) front, the front associated with a swift eastward current formed after the Kuroshio separates from the Japanese coast, which has recently been recognized as an important contributor to the PDO (e.g. Schneider and Cornuelle, 2005, Qiu et al., 2007). Analyzing the OFES hindcast output, Nonaka et al. (2006) demonstrated that the observed basin-wide cooling during the early 1980s in the North Pacific (Figure 2a) was accompanied by the southward shift and intensification of the two separate oceanic fronts: the Kuroshio Extension (KE) and the subarctic/Oyashio extension fronts. They attributed the subsurface cooling along the former front and the mixed layer cooling along the latter (Figure 2b) to the southward migration of the fronts, as the associated heat flux anomalies act to damp, rather than force, the temperature anomalies (reduced heat release into the atmosphere), indicating that sea surface temperature (SST) anomalies induced by the ocean feedback to the overlying atmosphere (Tanimoto et al., 2003).

Mechanisms that cause such migration of the oceanic fronts have not been fully explored due partly to their highly chaotic, nonlinear characteristics. An EOF analysis shows that wind-forced Rossby waves explain the variation in the jet over time but predict too broad a latitudinal structure (Taguchi et al., 2007). A further analysis with meridional scale separation suggests that the large-scale component of the decadal SSH anomalies in the OFES hindcast is well reproduced by the linear baroclinic Rossby wave adjustment theory (Figure 3a and b, page 13), but a much narrower structure of the KE variability results from the internal dynamics of the jet and recirculations (Figure 3c, page 13). Interestingly the large-scale and the frontal/recirculation variability exhibit nearly identical time series, which suggests that the wind-forced Rossby waves act as pacemaker regulating the intrinsic variability of the front (Taguchi et al., 2007).

Supplementary hindcast simulation with QuickSCAT wind stress forcing

In the QuickSCAT hindcast simulation, oceanic responses to the wind field including small scale features like the orographic wind in the lee of islands and near land boundaries are simulated well (Sasaki et al., 2006). For example, two branches of the South Equatorial Current in association with zonal band-like structures of the wind curl to the west of Galapagos Islands are realistically reproduced in OFES. Another example is the far-reaching Hawaiian Lee Countercurrent (HLCC) westward and in the lee of the Hawaiian Islands (Figure 4, page 13), for which two-way air-sea interactions are suggested to be important (Sasaki and Nonaka, 2006). In such interactions, the HLCC is further driven by the wind-stress curl induced by a warm SST band along the current, following the initial formation of the current at the Hawaiian Islands. This study demonstrates usefulness of the QuickSCAT simulation to investigate the impact of the small scale wind stress upon the ocean, which would never be possible without the fruitful combination of an eddy-resolving OGCM and satellite-observed high resolution wind forcing.

Summary and Discussion

A series of OFES simulations have been performed on the ES. The successful simulations provide us good opportunities to investigate not only mean fields but also variations with various temporal and spatial scales in the realistic simulated oceanic field including mesoscale eddies, narrow strong currents, and frontal structures, as briefly introduced in this article.

We have been extending the hindcast simulations up to date. Comparison of the OFES results to recent observational data from satellite and Argo profiling floats, for example, would provide us new insights about unsolved mechanisms responsible for ocean circulations and their variability. To share with the wider research community the treasure chest from OFES, we have started opening the outputs of the spin-up simulation, as a first step (http://www2.es.jamstec.go.jp/ofes/

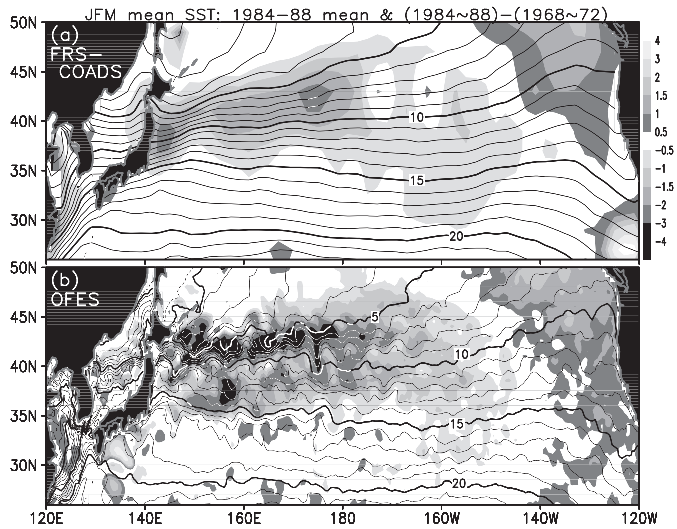

Figure 2. Wintertime (January-March) mean SST fields over the North Pacific based on (a) the observation (Frontier Research system Comprehensive Ocean and Atmosphere Data Set) and (b) the OFES simulation. Contours indicate the five winter mean for 1984-88 (every 1°C), and shade indicates the difference of that mean field from another five-winter mean for 1968-72, as indicated to the right of the top panel.

eng/). We will also open a portion of outputs from the hindcast simulation in the near future.

However, there exist some issues in the results of OFES to be solved in the near future. For example, occasional meandering of the Kuroshio south of Japan and the northwestward extent of the North Atlantic current are still unrealistic. To overcome these problems, we are trying to incorporate different parameterization schemes as well as a sea-ice model in OFES (Komori et al., 2005). Inertial mixing, tidal mixing, and non-hydrostacic processes, in addition, should be included into the future version of the high-resolution/ultra high-resolution model.

Together with the accompanying high-resolution atmospheric general circulation model (Ohfuchi et al., 2004) and the sea-ice model, a high-resolution ocean-atmosphere coupled simulation (Komori et al., 2007) is now executable on the ES, which is expected to improve predictability for high-impact phenomena with an assimilation system. Furthermore, an ocean biological model has been incorporated into OFES (Sasai et al., 2006) and will also be implemented in the coupled model in order to study predictability of marine ecosystem variability influenced by physical fields. More detailed analysis of these high-resolution models will lead us to the frontier of climate researche.

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From Griffies et al, page 3: Ocean Modelling with MOM

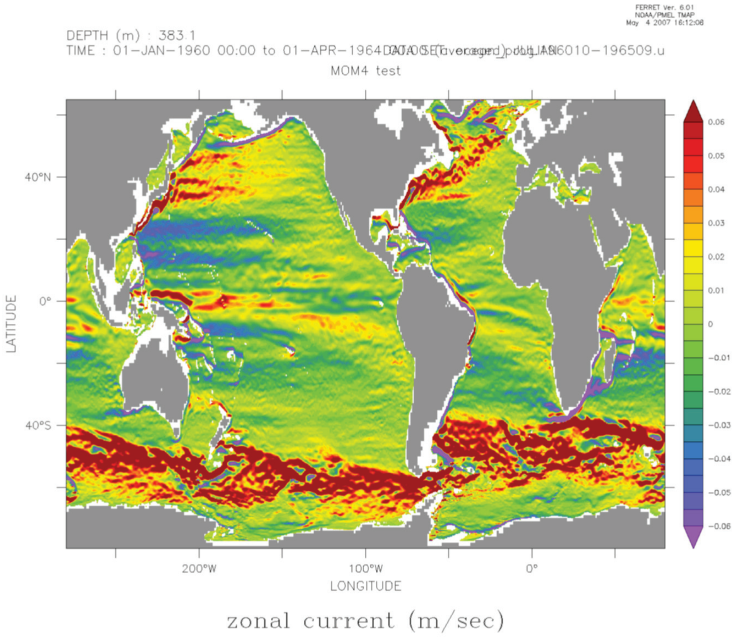

Figure 1: Five year mean zonal velocity at 400m in a global 1/4 degree MOM simulation. These currents show signs of the latitudinally alternating zonal jets described by Richards et al. (2007), which were seen in a 1/10 degree simulation as well as satellite altimetre observations

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From Saski et al (page 5): A series of quasi-global eddy-resolving ocean simulations

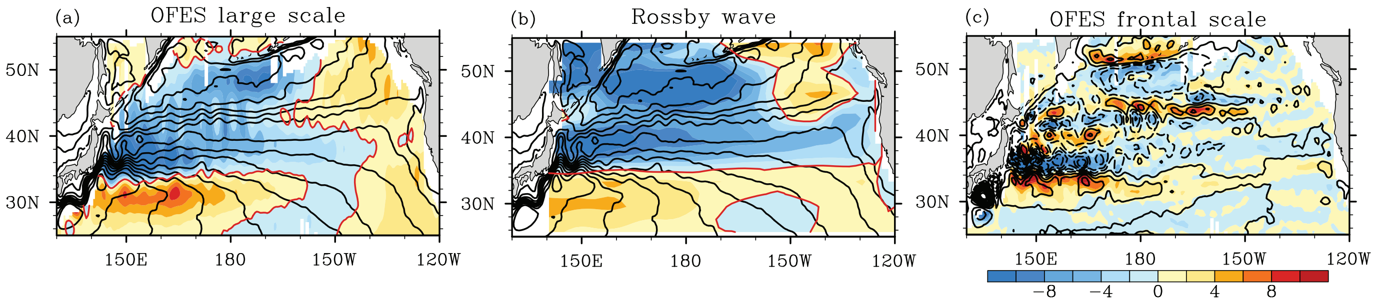

Figure 3. (a) Broad-scale component of the post (1984-1996) minus pre-shift (1968-1980) difference in OFES SSH (color shade in cm). Unfiltered OFES SSH averaged for both periods is superposed with black contours (at intervals of 10 cm). (b) Same as (a) but for SSH anomalies from the Rossby wave model (shade). (c) Same as (a) but for frontal-scale SSH (shade). Black contours designate differences in the unfiltered OFES SSH between the two periods with contour intervals of 5 cm.

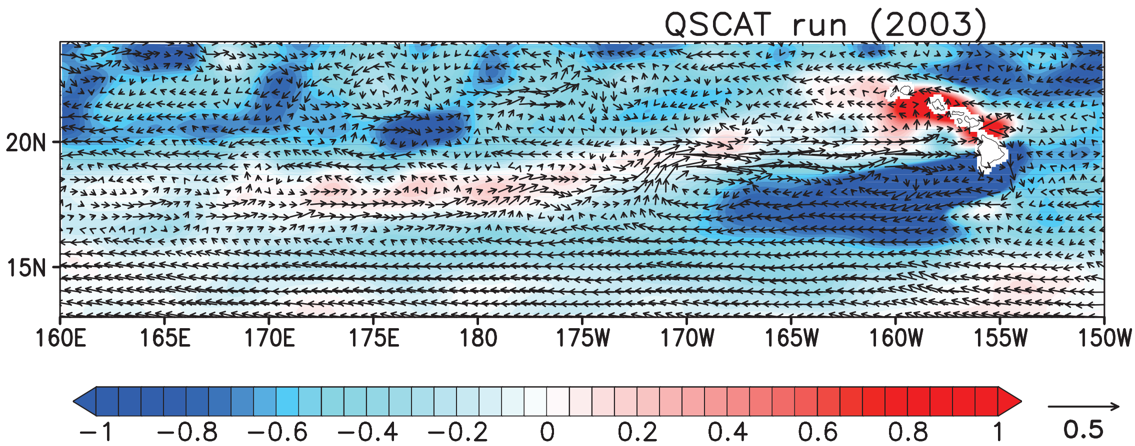

Figure. 4. Annual mean current vectors at 38 m depth (m sec^{-1}) and surface wind stress curl (color, unit: 10^{-7} N m^{-3}) in 2003 based on the OFES QSCAT simulation.