REQUEST FOR INFORMATION (RFI)

5 May 2016

Purpose of this RFI: At the behest of the Community Earth System Model (CESM) Science Steering Committee (SSC) we, the co-chairs of the CESM Ocean Model Working Group (OMWG), would like to request specific information and broader input from ocean model development groups to guide the choice of the next ocean component of the CESM. Of particular importance is your group's view on the possibility of replacing the current Parallel Ocean Program (POP) by your ocean model as the base model code of the next generation CESM ocean component. In your response, we would appreciate your assessment of the degree to which your model code and the collaboration with your development community can meet the criteria below. Other comments and feedback, for example on the technical requirements below, indication of near to intermediate term plans for model developments, or your views on possible synergies between your existing efforts and CESM, would also be welcome.

Motivation for this RFI: As we look beyond CESM2, it is necessary to formulate a plan for the next generation ocean model component. The POP model has been used as the base code of the ocean component of CESM for more than a decade. Despite many desirable attributes and advances in its physics over the years, aspects of the current dynamical formulation of POP are an impediment to improving the model skill and addressing cutting-edge climate research questions. POP will not be developed further by the Los Alamos National Laboratory, and progress on development of the dynamical core aspects of POP within the CESM community has stagnated. This RFI is one response to the Climate and Global Dynamics (CGD) Laboratory Advisory Panel (CAP) call for a reevaluation of the development path for the CESM ocean model – a path also supported in the latest letter from the CESM Advisory Board (CAB).

Strategy: A different ocean dynamical core will need to be adopted by the time CESM3 is released in 5 to 6 years. Therefore, the final choice will need to be made in about three years, but the situation to be avoided is to reach that point with CESM only capable of running with the POP code. Therefore, by the end of 2019 a provisional CESM3 ocean component based on the selected model code will be implemented, configured, and exercised at least to the point of demonstrating its additional science capabilities. The new base model code will be selected in 2016, and implementation will begin in earnest by January 2017 when a new ocean modeler and support scientists and software engineers are in place at NCAR.

The challenges in moving to a new base model are accompanied by an opportunity to re-examine the scientific requirements for ocean modeling within the CESM community. Such input from the CESM community was solicited through an e-mail survey early in 2016, and through extended discussions at the 2016 CESM OMWG winter meeting and the 2016 AGU/TOS/ASLO Ocean Sciences Meeting.

The high-priority technical requirements for CESM3 identified through this process will ideally include:

- Advanced dynamical core technical capabilities, including flexible vertical coordinates and resolution, advanced tracer advection schemes, natural boundary conditions on freshwater and tracers, and support for non-Boussinesq configurations;

- Model infrastructure and a development environment that provides strong support for collaborative model development with the university-based CESM community. This includes both structured programs such as Climate Process Teams and small group entrepreneurial projects;
- Strong support for both regional and climate modeling applications;
- Support for a wide range of resolutions and grids, and accompanying scale aware parameterizations;
- Ability to configure and run simpler idealized configurations for process modeling and educational applications;
- Compatibility with the CESM sea-ice model;
- Ability to interface with CESM coupled data assimilation system;
- Familiar post-processing and analysis capabilities (akin to CESM workflow tools).

Furthermore, the CAP report indicated that collaboration on ocean model development is essential, and having CESM rely on a 'handed-off' model for its ocean component is not a viable option. Instead, a strong collaborative relationship with a partner institution or consortium is favored. An ideal partner will possess strong expertise in ocean dynamical core development. It will also have both the capability and desire to actively collaborate with the CESM enterprise and its community to advance a community ocean model. In addition, it is expected that the partner group will have a strong and ongoing commitment from its "home" institution and/or agency sponsors to sustain the collaboration over the long term.

Criteria: Within the overarching goal of keeping the ocean component of CESM at the forefront, the ocean model should at least have the potential to satisfy the technical requirements listed above and its published solutions should be comparable to those of the present POP in the context of the Coordinated Ocean-ice Reference Experiments (CORE). Additional desirable features include a modern code base that adheres to software engineering best practices; scalability and computational performance on modern architectures that is comparable to, or better than, POP; a commitment to comprehensive model documentation; and state-of-the-science parameterizations (comparable to those in the present POP) suitable for use in coarse resolution climate models. An expectation would then be that a configuration of the chosen model could satisfy CESM science requirements for CESM3.

In summary, it is hoped that an ocean component of the CESM would satisfy most of the following criteria to some degree:

- *A strong partnership between the developers of the model and the CESM community;*
- *A strong commitment to sustained collaboration in model development from the model's institutional home or consortium;*
- *Timely and unfettered access to new developments;*
- *Meet or have the potential to satisfy the technical requirements listed above;*
- *State-of-the-science parameterizations (comparable to those in the present POP) suitable for use in coarse resolution climate models;*
- *Published solutions showing a model version that is comparable to POP in the context of Coordinated Ocean-ice Reference Experiments (CORE);*
- *A realistic expectation that a configuration of the model would satisfy CESM3 science requirements in a timely manner;*

- *A modern code base that adheres to software engineering best practices with scalability and computational performance on modern architectures comparable to, or better than, POP;*
- *A commitment to comprehensive model documentation.*

Process and Timeline: The SSC will choose a model base code that will become the provisional replacement for POP based on the recommendations of a small independent advisory panel (AP, to be led by F. Bryan) and the OMWG. The AP will present a preliminary evaluation of the responses to this RFI at the 21st Annual CESM Workshop in Breckenridge on 21 June 2016. Therefore, responses to this RFI would be most helpful if received by June 3, 2016. During this meeting, responders can choose to take the opportunity, or not, to provide additional information and to answer emerging questions, either in person or remotely. Starting with this meeting, the AP will solicit input from the other CESM communities, particularly from the sea-ice, biogeochemistry, land-ice, and paleo-climate communities.

Following the Breckenridge meeting, the AP is likely to initiate direct discussions with responders, the OMWG, and other relevant parties, before submitting its recommendation to the SSC on 2 September 2016. The SSC and current OMWG co-chairs will jointly make a decision by early October 2016.

Community and Partnership: As a community modeling enterprise, CESM development relies on partnerships that, ideally, build on a strong desire or willingness for mutually beneficial collaboration of scientists and software engineers; joint decision-making in relevant model developments; timely and unfettered access to new developments; open lines of communication at all levels; responsiveness to the needs of the CESM community as expressed through the OMWG. The CESM community consists primarily of scientists and software engineers from NCAR, national universities, and government labs (especially DOE). Access to such community might provide the partner institution with a broader group of developers and users than it currently has.

Resources: There will be an additional ocean modeler as well as science and software engineering support at NCAR for the transition to the new ocean model, starting in January 2017. These resources will be directed, as needed, to facilitate scientific collaborations with the partner group; to design and build the interfaces between the new ocean dynamical core and other CESM components; to assist in the porting of parameterizations from POP to the new dynamical core and configuring of a CESM3 provisional ocean component; to adapt the new model to the evolving high-performance computing landscape; to interface with CESM data assimilation infrastructure; to address emerging challenges with pre- and post-processing of grids and topographies for paleo-climate; and to provide general help with, e.g., biogeochemical tracer interfaces and sea-ice coupling.

Additional available resources will be dedicated to engaging the university community in all aspects of ocean model development.

Response from NOAA/GFDL MOM6 Developers

Alistair Adcroft, Robert Hallberg, and Stephen Griffies
June 3, 2016

The MOM6 development team (the M6DT, represented by Adcroft, Hallberg, and Griffies) enthusiastically welcomes this RFI from the CESM OMGW. MOM6 would be an excellent choice for the ocean model code used in CESM3. In this response, we outline aspects of MOM6 relevant for your considerations.

Dynamical Core

MOM6 is a hydrostatic primitive equation ocean model with a particular emphasis on earth system modeling relevant characteristics, such as exact scalar conservation, robust performance, and efficient application to tracer-heavy configurations. It has been utilized for applications ranging from idealized process studies, regional/basin configurations, and global climate models. Notably, most of GFDL's contributions to CMIP6 will use a MOM6 ocean component.

MOM6 is built around a dynamic core making use of an Arbitrary Lagrangian Eulerian (ALE) vertical remapping approach to facilitate a wide range of vertical coordinates (e.g., z*, p*, isopycnal, terrain following, hybrid). It also offers the option of a traditional isopycnal layered model approach. MOM6 combines the computational efficiency of a structured (logically rectangular) C-grid with flexibility arising from generalized orthogonal horizontal coordinates (e.g., tripolar grids are routinely used at GFDL). Notably, the C-grid stencil of MOM6 has advantages over the B-grid of previous MOM.x versions, particularly for representing the complex land/sea boundaries. The momentum equations are written in the vector invariant form and a range of second-order discretizations are available. The dynamics are mode split in which the explicitly time-stepped barotropic mode is sub-cycled within a baroclinic step (Hallberg and Adcroft 2009). The barotropic equations are fully nonlinear (free surface height or bottom pressure), allowing for tidal motions with astronomical forcing and use of natural boundary conditions for fresh water.

The ALE dynamical core utilizes remapping in the vertical with high-order reconstructions schemes up to 5th order in accuracy (White and Adcroft, 2008). This approach permits the use of generalized vertical coordinates (White et al., 2009) and hybrid coordinates (Bleck, 2002). The vertical direction is fully implicit and unconditionally stable to vertical motions and diffusive processes, thus allowing for arbitrarily thin layers. Pressure gradient errors are minimized in general coordinates using an analytically-integrated finite volume pressure gradient force (Adcroft et al., 2008).

The MOM6 dynamic core uses the continuity equation to capture gravity wave dynamics, and sub-cycling of the baroclinic dynamics allows a longer tracer and thermodynamic timestep than needed for adiabatic dynamics. This approach is perfectly conservative of tracers and

mass/volume, and can greatly improve the computational performance of tracer-heavy Earth System models. Tracers are advected with either second-order (PLM) or third-order accurate schemes (PPM), with more choices planned. MOM6 supports both Boussinesq (volume conserving) and non-Boussinesq (mass conserving) kinematics. MOM6 uses the natural surface boundary conditions and riverine inputs for both water substance and tracers. MOM6 has the ability to wet and dry conservatively (scalars are conserved to computational round off), which is of particular importance for simulating regional sea level studies, estuaries, and dynamic ice sheet / ocean interactions of primary importance for projections of sea-level rise (e.g., Goldberg et al., J.G.R. 2012).

Bathymetric depths can take continuous values without quantization and is independent of the choice of vertical coordinate. Sub-grid 3D representations of topography for use in the baroclinic model are under development (Adcroft, 2013) building on the long-established practice in MOM6 of using actual channel widths for interbasin exchange (e.g. Gibraltar Strait is 12 km wide, even in a 1° model).

Vertical and Lateral Physical Parameterizations

Lateral subgrid parameterizations include an eddy-induced advection scheme based on Gent and McWilliams (1990); an along neutral-direction diffusion of tracers (Redi, 1982; Griffies et al., 1998; Adcroft et al., in prep); a modulation of mesoscale parameterizations via resolution aware coefficients (Hallberg, 2013); a second-order closure of subgrid mesoscale eddy energy (Jansen et al., 2015); a closure for backscatter by subgrid mesoscale eddies (Jansen and Held, 2014); a parameterization of submesoscale mixed layer eddies (Fox-Kemper et al., 2008); flow- and scale-aware Smagorinsky Laplacian and Biharmonic viscosities (Griffies and Hallberg, 2000).

Vertical parameterizations (single column) include several planetary boundary layers schemes including KPP (via CVMix), and energy-based PBL (Hallberg, in prep). A Kraus-Turner-Niiler bulk mixed layer (Hallberg, 2003) is used in stacked-shallow water mode (isopycnal layers). A shear-dependent mixing scheme (Jackson et al., 2008) has been calibrated against DNS and works well for overflows, the equatorial undercurrent and shear at the base of the mixed layer. Bottom generated mixing is represented with a variety of energetically constrained parametrizations such as Jayne and St Laurent (2001), Polzin (2009), Melet et al. (2013), as well as energetically constrained bottom-drag driven mixing following Legg et al. (2006). Vertical mixing is implemented via fully time-implicit diffusivity/viscosity and can be readily extended to include more schemes. Short-wave absorption is calculated via an N-band scheme with variable optical depths dependent on chlorophyll concentrations or prescribed water properties. Geothermal heat flux can be included both as a direct heat source and as an energy source for mixing in the BBL.

Miscellaneous Features and Allied Codes

Ongoing research (with funded post-doc at GFDL and another at NCEP) is concerned with coupling Wavewatch III to MOM6, along with attendant upper ocean wave-induced mixing schemes. This work is targeted for global climate, SI forecasting, and tropical cyclone research.

CMIP6/OMIP diagnostics have been implemented in MOM6, making use of the CMOR names recommended by PCMDI. MOM6 has additional diagnostic features, with near-term plans for tools such as water mass analysis, Lagrangian floats, and offline tracers. Many of the analysis scripts used for MOM6 evaluation make use of Python notebooks that are distributed as part of the MOM6 example test cases.

Ongoing collaborations with regional/basin model developers are extending the open boundary conditions and nesting capabilities of MOM6, compatible with similar features available in ROMs.

GFDL has active biogeochemistry activities, including the development of the TOPAZ (Dunne et al, 2013) and COBALT (Stock et al, 2014) models. Each of these models sits outside of the ocean model, and have been coupled to MOM6 as part of our ongoing earth system model development for CMIP6.

GFDL has active sea-ice model development, with version 2 of the Sea Ice Simulator (SIS2) having been developed in line with the C-grid stencil of MOM6. SIS2 shares much with its SIS1 predecessor (Winton, 2000). However, it makes use of many physical parameterization features from CICE.

GFDL has active iceberg (Martin and Adcroft, 2010) and ice-shelf development (Goldberg et al., 2012), each of which impacts on the development of MOM6, particularly given the aim for ice-shelf grounding lines to evolve.

MOM6 Software

The MOM6 code base reflects a commitment to modern software engineering practices as appropriate for an ocean-climate model with both active development and key production applications (such as GFDL's coupled climate models). Foremost among these practices is a robust testing protocol. The protocol involves an extensive suite of test cases, ranging from idealized process configurations to short runs of full ocean-climate models. The results of these tests are monitored for bitwise replication of solutions across processor count, restarts, and memory allocation mode for runs using the same computer and compiler settings. If CESM were to adopt MOM6, the M6DT would encourage the addition of CESM configurations to the MOM6 testing protocol.

The MOM6 code base uses a moderate object-oriented approach, reflecting the constraints of performance and the Fortran2003 language standard. All information is passed into subroutines via arguments, either standard F90 data types, or in module "control structures" which encapsulate the private parameters and other information of a particular module. There is no use

of module variables in MOM6 (apart from handles for code timers). All module "use statements" for data types or procedure interfaces are made explicit by making use of the "only" flag. This approach makes it relatively straightforward to track the flow of data through the MOM6 code, and facilitates development and debugging.

MOM6 exhibits full parallelization and scalability via a combination of message passing and openMP directives. The message passing is accomplished through GFDL's Flexible Modeling System (FMS) infrastructure, although the FMS calls in MOM6 are wrapped in such a way that it should be feasible to utilize a different infrastructure instead (e.g., ESMF) as a non-disruptive compile-time selection. On NOAA's computers MOM6 scales to about 10x10 points per processor, although this will vary across machines.

Documentation is a critical consideration for MOM6. In MOM6, documentation starts with the model code itself. All MOM6 parameters are automatically logged (with explanatory comments, units and default values) into a file that can be reused as the input for a second MOM6 giving identical results, making it easy to determine what was actually used. Within the code, all arguments and variables are (or at least should be) documented with comments describing the variables, including units and sign conventions as appropriate. Increasingly, these comments use the dOxyGen syntax to allow consistent version-controlled web-pages to be generated from the code itself. Other documentation can be found on use-oriented web-pages tied to the MOM6 GitHub repository or hosted at GFDL. However, it should be noted that the documentation of MOM6 is an ongoing process. We are actively pursuing such documentation both in the peer-review literature and through general use technical reports.

MOM6 Open Development and Collaborations

MOM6 builds upon the decades-long tradition of community ocean modeling, and is available without restriction. Moreover, MOM6 has adopted a set of protocols to facilitate community contributions, while still giving individual groups and users the ability to innovate on separate branches until such time as they wish to share their work.

The members of the M6DT have long enjoyed mutually beneficial collaborations with the NCAR and CESM ocean modeling communities through such projects as NSF/NOAA-funded Climate Process Teams, the Coordinated Ocean/sea-ice Reference Experiments, the CVMix project, as well as other efforts. Were CESM to select MOM6, we are confident that it would accelerate NCAR/GFDL exchange and evaluation of innovations in ocean-climate modeling practice. At the same time, the M6DT feels that it is useful for the vitality and diversity of the U.S. climate modeling community that CESM use a configuration of MOM6 with specific distinctions (e.g., resolutions; parameterizations; vertical coordinate) from that used by GFDL or other global climate modeling centers.

MOM6 enjoys the ongoing institutional support of NOAA/GFDL, including hard-money support for the key developers of MOM6 at GFDL, and ongoing software support of MOM6 from GFDL's Modeling Systems group, both directly and via the Flexible Modeling System (FMS).

MOM6 is widely used for scientific applications at GFDL (e.g., CMIP6, coupling to cryosphere), and will be the basis of planned ocean modeling contributions from GFDL to other parts of NOAA, including NCEP. There is every reason to expect that MOM6 will continue to be well supported in coming years.

MOM6 uses an "open development" paradigm that exploits the capabilities of modern version control software (git) to provide immediate access to the latest MOM6 capabilities to anyone, and conversely to facilitate contributions from scientists worldwide. The MOM6 development team is centered at NOAA/GFDL, but includes contributors from academic institutions both within the U.S. and internationally. Whereas previous versions of MOM used a release-based community-access paradigm with a GFDL gatekeeper, the very latest MOM6 versions of the GFDL/master version are openly accessible via GitHub.

Were CESM to adopt MOM6, the M6DT envisions there being a distinct CESM/master version of MOM6 (perhaps served via GitHub) that would be under quality control of the CESM group. Additionally, we envision a concerted effort to keep the two branches synchronized, exploiting the excellent capabilities of git in this regard. There will likely also be several other major groups with actively developed branches of MOM6 (e.g., a branch centered on climate modeling efforts in "Institution A", an academic coastal modeling consortium branch, and/or an operational forecasting branch). It is important that each branch controls what is pulled into it, because testing of key configurations requires access to specific computers, compilers and/or access to other coupled components that do not share the open code-sharing policy of MOM6. However, it is essential to emphasize that the M6DT is committed to take whatever steps are necessary to avoid branching into irreconcilably different versions of MOM6. That is, we envision a unified, transparent, and collaborative MOM6 effort across all groups.

Closing Comments

Development continues with MOM6 at a rapid pace. Were CESM to adopt MOM6, it would represent an important and exciting collaboration between GFDL, NCAR, and the broader CESM community. GFDL scientists and management unanimously agree that MOM6 would be an ideal match for CESM. Conversely, we believe that CESM would be a vital and stimulating partner in MOM6 development, and would spearhead novel and leading ocean and climate science.

Our response to your RFI hopefully offers a useful outline of the MOM6 features and its overarching development framework. Alistair Adcroft will attend the June 2016 CESM meeting in Breckenridge, where follow on information can be shared. Further discussions are anticipated and welcomed as you pursue the decision making process for the CESM3 ocean component.

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