# Arbitrary Lagrangian-Eulerian (ALE)

# Working Group Meeting

Silver Spring

9-10 May 2017

## Executive Summary

A one-and-a-half day working group meeting was held on 9-10 May 2017 in Silver Spring, MD, as a follow-on to the larger October 2017 workshop on ocean models that employ the ALE (Arbitrary Lagrangian-Eulerian) method for general vertical coordinates. The working group meeting included broad representation by NOAA, Navy, NCAR, NASA and university ocean modelers with the goal of discussing the feasibility of a common ocean model framework for operations and research, suitable for both high-resolution, short time scale work as well as coarser resolution, longer time scale modeling.

Speakers presented their organizational and modeling needs, and the group created a notional list of requirements for a common community ALE-based ocean modeling effort, which should:

* support as many agencies and modeling centers as possible, testable by each center’s own metrics
* be an efficient, scalable code to permit high resolution modeling
* be a global multi-scale effort, capable of supporting nests for regional modeling
* consist of modular code so that ALE modeling groups in NASA GISS and DOE LANL could exchange modules, and thus enhance development
* allow many eyes throughout the community to look at the model, leading to model improvements

The group agreed on the need to converge to a single, modular ocean modeling framework for all time scales. To address this need, the group agreed to perform preliminary feasibility tests of MOM6 and HYCOM with the goal of merging HYCOM features into MOM6, and to develop a formal proposal. Pending successful feasibility results, the working group recommended the proposal be presented for funding to enable progress toward this goal.

## Introduction

A one-and-a-half day working group meeting on ocean models that employ the ALE (Arbitrary Lagrangian-Eulerian) method to permit general vertical coordinates was held in Silver Spring on May 9-10, 2017. The working group meeting was a follow-up to an ALE workshop held at NOAA/NCWCP in October 3-4, 2016. A key point that emerged from the October 2016 workshop is that ALE is versatile and permits general vertical coordinates including traditional z, isopycnal, and terrain-following coordinates, as well as hybrid combinations of the former and other creative treatments yet to be formulated and explored. A general feeling that the time for ALE modeling has arrived permeated the October 2016 workshop. The October 2016 workshop recommended that the ALE community consider a code merger between HYCOM and MOM6, bringing the strengths of each to a common code base. The May 2017 working group meeting built upon this recommendation with a focus on talks that discussed the specific agency/institutional needs that need to be considered and met in such a merger, the need for metrics to determine whether models met agency needs, and plans for going forward. The need for code modularity was stressed, to allow for code-sharing with other ALE models such as the NASA GO2 model and the DOE MPAS-Ocean model, as it was in the October 2016 meeting.

## Summaries of Talks

### Agency perspectives on collaboration potential and drivers

An agenda for the May meeting listing all of the presentations is included later in this document.

The May 2017 working group meeting began with a summary of the October 2016 workshop, given by Brian Arbic and Avichal Mehra. The October 2016 workshop brought together developers and users of several ALE models, from several modeling centers as well as academia. The October 2016 workshop was a follow-up to Town Hall meetings, held at large AGU and AMS meetings, on the future of ocean modeling. The October 2016 meeting discussed the future of ALE modeling, and the opportunities for collaboration between different modeling groups. The convergence of interests between long-term and short-term forecast communities was noted, as was the launching of ambitious programs for global forecasting by NOAA and the US Navy, for instance the Department of Defense National Earth System Prediction Capability (ESPC), and the NOAA Unified Modeling Framework. Both NOAA and the US Navy envision operation of a next-generation ocean model by FY23. The October 2016 workshop recommended code sharing, community building, consideration of a code merger between HYCOM and MOM6, and several issues related to model performance and future development, for instance the physics of boundary layers, and the value of funding different approaches to ALE modeling.

The second May 2017 working group meeting talk, given by Jessie Carman, was on the national ESPC effort and inter-agency collaboration. The ESPC represents an effort to bridge the gap for decision support between synoptic, or daily/weekly, timescales, with longer time scales such as seasonal, interannual, and decadal time scales. There is an increasing realization that using the same model for short- and long-scale predictions yields numerous benefits and efficiencies.

The perspective from the office of the Oceanographer of the Navy, given by Dave McCarren, is that there is a need to make the ocean model more scalable, so that it does not take up such a large percentage of the available cores as it does now. The Navy needs scalable models, to support high spatial resolution, coupling with ice models (especially in the Arctic, a region of intense current interest), and data assimilation.

As discussed by Hendrik Tolman, NOAA has recently published white papers on the benefits of unified modeling. NOAA NCEP views the partnerships with GFDL and with NRL as hugely beneficial for both its near-real-time and seasonal prediction efforts. NCEP needs a closer assessment on the best approach for a single framework and how to fund the work as it cannot be a major sponsor of the ocean part of the unified model. NCEP supports the multi-model ensemble concept by allowing diverse code bases under a unified framework, and would leverage other centers for model development. Forecasters need multi-model ensembles to communicate uncertainty.

### Modeling state: HYCOM/MOM6

As noted in a discussion led by Alan Wallcraft, efforts to perform direct comparisons of HYCOM and MOM6 simulations in nearly-identical configurations are already underway. NOAA/GFDL has succeeded in running MOM6 on a 1/12th degree HYCOM grid, with simultaneous atmospheric and tidal forcing. NRL has attempted to run MOM6 on a 1/12th degree HYCOM grid, but so far has not succeeded due to issues that should be fixable. Alan Wallcraft plans to travel to GFDL in June to collaborate on getting MOM6 running on the HYCOM grids and on Navy machines. This trip will be discussed in more detail later in this document.

Carlos Lozano has led an effort at HYCOM-MOM6 comparison at NOAA NCEP. He has been running the models in a global 1/12th degree, 32-layer configuration, and comparing the HYCOM RTOFS simulations to Argo observations.

### Agency/office requirements on ocean models; interest in participation

Steve Penny talked about data assimilation, which is a critical topic for operational centers such as NOAA NCEP and NRL/NAVO. There are two major camps in data assimilation-one espousing Ensemble Kalman Filter methods, and the other espousing variational methods including the adjoint, and the trend has been towards merging these into hybrid methods. Penny sees multiple spatial and temporal scales as one of the approximately 6 big challenges facing the ocean and coupled data assimilation community today, and recommends active collaboration between modeling and data assimilation communities throughout development.

Alan Wallcraft discussed needs of NRL and NAVO. NAVO needs better “feature placement” of mesoscale eddies. The Navy is most concerned with acoustics and near-surface currents. The Navy’s interest in the National ESPC program is focused on 90-day forecasts for strategic guidance. Wallcraft noted that MOM6 and HYCOM already share many features. However, in order for MOM6 to meet Navy operational needs some of its existing capabilities, including its non-Boussinesq capability, would need to be extensively tested on global high horizontal resolution grids and several capabilities currently available in HYCOM would need to be added to MOM6, including the use of terrain-following coordinates in shallow seas, spatially varying target layer densities, robust support for tides, 3DVAR data assimilation, the use of steric sea surface height as a diagnostic field, atmospheric pressure loading, the ability to nest for regional modeling, and higher-order advection operators. Wallcraft noted that all of this would represent a substantial effort, appropriate for a multi-center NOPP project.

Carlos Lozano and Avichal Mehra gave presentations on NOAA NWS operational requirements for a global ocean model. NWS desires efficient and accurate (numerical) representation of mesoscale ocean variability from shelves to the deep ocean driven by atmospheric forcings; river and runoff; tidal forcings; ice melting, freezing, and drift; and surface gravity waves. NWS desires a non-Boussinesq formulation, and like NRL/NAVO, will provide data assimilation expertise for ocean forecasting. For NWS seasonal forecasts a lower resolution version of MOM6 will be used. NWS real-time forecasting will use high-resolution ocean models, as in the present RTOFS system. Because NOAA NWS will run this model on an operational basis, the model must be “bulletproof;” i.e. robust enough to run in near-real-time on a regular basis. This also applies to use of the model for Navy operational ocean modeling. Lozano and Mehra again emphasized the need for reduced complexity of the NCEP Production Suite, as well as a unified, collaborative strategy for model development across NOAA. The JEDI system for data assimilation is part of this effort.

Bob Hallberg and Alistair Adcroft presented an overview of their MOM6 development efforts. MOM6 represents a vision for a community ocean model. GitHub allows for immediate dissemination of improvements. Robust testing, documentation, and community engagement are all key features of the MOM6 vision. GFDL sees NRL and NOAA NCEP as providing operational/data-assimilation expertise to the proposed HYCOM/MOM6 merger effort. NCAR will use a complementary (not identical) configuration to that used by GFDL, and, like GFDL, will focus on longer time scales. GFDL notes that managing the collaboration will be one of the biggest challenges for this effort. Different centers have different needs, and everyone is stretched for time.

Frank Bryan discussed NCAR ocean model needs as well as the contributions they make to the modeling community. NCAR provides coarse-resolution (about 1 degree) ocean models for long-time-scale studies of the Earth system, as part of the Community Earth System Model (CESM) framework. CESM modeling efforts include even coarser resolution configurations for paleoclimate studies, as well a small number of higher-resolution configurations (of order 1/10th degree) for studying the role of ocean eddies in coupled atmosphere-ocean simulations. NCAR does use data assimilation, for decadal prediction. The adoption of MOM6 will represent a new direction for NCAR, which has not previously used ALE models, and NCAR scientists will have to “learn the ALE psychology” as they proceed. Additionally, there will be a considerable effort to educate CESM users in both the ALE based model formulation and analysis simulations using ALE based models. NCAR expects to expend considerable research effort in the area of scale-adaptive lateral closures to ocean modeling.

Rainer Bleck and Darren Engwirda discussed NOAA ESRL and NASA GISS needs for, and contributions towards, ALE ocean modeling. Both centers run simulations for long-time-scale forecasts, and both centers are involved in ALE model development. NOAA ESRL is running a version of HYCOM on an icosahedral grid, while NASA GISS is running a new ALE model (GO2). Both Bleck and Engwirda emphasized their plans to continue to run their own ALE models (not the proposed HYCOM/MOM6 merger code), thus contributing to the important goal of maintaining model diversity. At the same time, if the proposed HYCOM/MOM6 merger code is written in a modular manner, then it will be easy for Bleck and Engwirda to swap parts of code in and out, thus contributing greatly to the quality of the HYCOM/MOM6 code.

Brian Arbic briefly discussed the contributions that academia makes towards large-scale ocean modeling efforts. Academia serves as a training ground for young scientists, some of whom participate in process studies that can lead to important improvements in ocean models, and some of whom undertake significant model-observation comparison studies. Another contribution that academia can make towards ocean model development is the entrainment of young scientists with strong computational science backgrounds into the field. The number of ocean model developers is small and needs to be increased. Steve Penny concurred with these points.

## Distillation of content:

To summarize the first day of the working group meeting, presentations on ALE modeling were given by practitioners from several agencies and modeling centers. The needs of different agencies and modeling centers, as well as the contributions they can make towards the ALE modeling community, were discussed. There is general interest on the part of NOAA and the US Navy in conducting further tests on the feasibility of a HYCOM/MOM6 code merger, and there is general interest on the part of other agencies and centers (e.g., NASA GISS, and, we hope, DOE) in creating modular codes to promote code sharing between HYCOM/MOM6 and other ALE models such as GO2 and MPAS-Ocean. Tests of HYCOM and MOM6 in identical configurations will be conducted shortly.

In the discussion at the end of the first day of the workshop, the following points were made about a potential HYCOM/MOM6 merger:

* it should continue to be a community ocean model, based primarily on MOM6 with added HYCOM capabilities
* it should satisfy and involve as many agencies and modeling centers as possible
* each center should test the code with its own metrics
* it should be done with modular code so other ALE modeling groups in NASA GISS and DOE LANL could exchange modules and so that it could form the framework for other ALE-based ocean model designs
* it would allow many eyes throughout the community to look at the model, leading to model improvements
* it should be a global multi-scale effort
* it should be capable of supporting nests for regional modeling
* it should be an efficient, scalable code

### Agency motivations to participate

There are several motivations underlying agency participation in this project.

a. Program managers are looking for efficiencies in times of tight agency budgets. It is more efficient to maintain one common, modularized code base than two similar code bases (e.g., HYCOM and MOM6).

b. A common, modularized code base implies many “eyes on the model”; in other words, many model users and developers will examine the proposed HYCOM/MOM6 code base, especially because routines can be swapped in and out from other models such as GO2 and MPAS-Ocean. The many “eyes on the model” also includes participants looking at the simulation outputs, and comparing them to observations, all of which will lead to model improvements.

c. A common code base makes it much simpler to upgrade the code when new machines are put into place; it precludes the need for updating multiple codes as would need to be done now at, for instance, NCEP, which currently maintains two ocean codes (HYCOM and MOM4).

d. The new code base will help some agencies to modernize their code base relative to the comparatively old codes that they are currently using. The proposed merger project could be a route for the Navy, and for NOAA NCEP, to meet their stated goals to upgrade their ocean model dynamical core by FY23.

e. A common, shared code base will allow some agencies to borrow from the strengths of other agencies. For example, the Navy expertise in data assimilation will allow for development of assimilative codes that will also be useful for NCEP. Similarly, the development of the MOM6 code at GFDL will ease the pressure at other modeling centers (e.g., the US Navy, NCAR, and NCEP) to develop ocean codes all by themselves; they will instead be able to focus on adapting the HYCOM/MOM6 merged code to local agency/center needs.

f. A common code base can be used for “unified modeling” across a wide range of spatial and temporal scales—another type of efficiency that is increasingly being recognized as important. For instance, in the atmospheric modeling community, the boundaries between weather models and seasonal-to-interannual prediction models are increasingly blurring. With this document we are making a similar argument for ocean models.

### Agency contributions/expertise

NOAA/GFDL has created the existing MOM6 code base, building upon in-house ALE modeling expertise. GFDL will develop code-testing protocols, and has already provided several working configurations. Finally, GFDL will provide oversight on the dynamical core and the code repository. NOAA/ESRL provides additional ALE modeling expertise, while NOAA/EMC provides expertise in real-time forecasting, data assimilation, coupling frameworks, and code management. NOAA/NOS provides coastal modeling operations and expertise, along with connections to coastal modeling communities, within US coastal waters. NCAR provides a network to a large user community in academia and elsewhere, connections to biogeochemistry support, investment in community support (e.g., tutorials for young scientists), and development of model physics. The Navy hosts the existing HYCOM database, and has a history of expertise in ALE modeling, data assimilation, real-time forecasting, and coastal modeling at locations around the world. GISS brings expertise in ALE modeling, numerical model development, access to a different coupled earth system model framework, and development of a different ALE modeling code base (GO2). Academic partners contribute expertise in ALE modeling, process studies, model evaluations, and training of young scientists.

## Next Steps

### Proof-of-Concept Test

Alan Wallcraft will visit GFDL and, in collaboration with GFDL scientists Bob Hallberg, Matt Harrison, and Alistair Adcroft, develop initial tests of MOM6 on ¼ and 1/12th degree grids. The ¼ degree test will be run for 10 years, while the 1/12th degree test will be run for 5 years. NCEP may send someone to GFDL during Wallcraft’s visit there. It is important to test whether MOM6 functions well when run in “semi-operational” mode (short time scales and high spatial resolution). The computational speed/scalability of MOM6, and its ability to perform an initial simple forecast, will also be tested. For the latter, we will test whether we can get incremental insertion from NCODA working. We will test a 5-day forecast from a Nowcast that looks reasonable.

Separately, Brian Arbic and his postdoc Joseph Ansong will work with Wallcraft to develop one- and two-layer simulations of tides in MOM6. Ansong has already developed MOM6 into a one-layer tide model, with great success, on University of Michigan machines. Wallcraft will work to adapt these results to the HYCOM grids. The two-layer tide runs will represent a clean test of the non-Boussinesq capabiliities of MOM6.

### Develop a Proposal

After the proof-of-concept test, we plan to develop a proposal that includes the following elements:

* Phase one testing - Make vertical coordinates as similar as possible, compare parameterizations, examine basin configurations, and use the “correct” equation of state for higher resolution runs.
* Run standard metrics for comparison. Brian Arbic and collaborators plan to compare eddy kinetic energy to altimetry and drifter observations, and to compare the internal tide sea surface height signal to altimetry data. The latter comparison will be an excellent indirect test of the “inviscidness” of model numerics; in models that are too viscous, the internal tides do not propagate as far as they do in altimetry data. Modeling centers will run their own suite of standard ocean model metrics.
* The proposal will provide a detailed description of partner contributions. For instance, NRL and NOAA NCEP will provide data assimilation expertise, etc.
* The proposal will include a description of the deliverable and the desired end state. Both of these can be fine-tuned later. For now, we envision a deliverable that is a version of MOM6 (with HYCOM and other code merged in) that provides a suitable backbone for ocean modeling at NOAA, Navy, and NCAR. We envision that the code base will be modular so that NASA GISS GO2 users as well as DOE MPAS-Ocean users can swap code components in and out.

The project proposal will also be modular in that a minimal path forward can be ascertained, as well as a maximal plan. This will permit progress with minimal budgets as well as flexibility to take advantage of larger budgets.

The project proposal will take into account the specific physics and features (e.g., tides, sea ice, data assimilation) that are needed by particular agencies/centers. The proposal will take into account how the potential code merger fits into the ESPC. The project will also account for both human and computational resources. For example, a “maximal” plan will likely lead to hires of new computational scientists in at least some of the centers.

Finally, the project will take into account the fact that computer architectures continue to change. In a “maximal” project, academic centers would look to entrain more young computational scientists into the field of ocean model development.

### Future model discussion issues

The proposal will discuss creating a forum for configuration management and code repositories, drawing connections between various center versions and configurations. This forum should also discuss issues such as ocean model metrics. While it is likely that each agency and center will have its own metrics, sharing and comparing metrics will be beneficial. As noted previously, the proposal will outline a modular code, such that it will be simple for subroutines and modules to be added or switched by model users.

### Acronyms:

3DVAR: 3-Dimensional Variational data assimilation

AGU: American Geophysical Union

ALE: Arbitrary Lagrangian-Eulerian

AMS: American Meteorological Society

CESM: Community Earth System Model

DOE: Department of Energy

EMC: Environmental Modeling Center

ESPC: Earth System Prediction Capability

ESRL: Earth System Research Laboratory

GFDL: Geophysical Fluid Dynamics Laboratory

GISS: Goddard Institute for Space Studies

GO2: Goddard Ocean Model 2

JEDI: Joint Effort for Data Assimilation Integration

HYCOM: HYbrid Coordinate Ocean Model

LANL: Los Alamos National Laboratory

MIT: Massachusetts Institute of Technology

MOM6: Modular Ocean Model version 6

MPAS-Ocean: Model for Prediction Across Scales - Ocean

NASA: National Aeronautics and Space Administration

NAVO: Naval Oceanographic Office

NCAR: National Center for Atmospheric Research

NCEP: National Centers for Environmental Prediction

NCODA: Navy Coupled Ocean Data Assimilation system

NCWCP: NOAA Center for Weather and Climate Prediction

NOAA: National Oceanic and Atmospheric Administration

NOPP: National Oceanographic Partnership Program

NOS: National Ocean Service

NRL: Naval Research Laboratory

NWS: National Weather Service

OSTI: Office of Science and Technology Integration

ROMS: Regional Ocean Modeling System

RTOFS: Real-Time Ocean Forecast System

### Workshop Organizers:

Brian Arbic, University of Michigan

Jessie Carman, NOAA/OAR and National ESPC Office

Robert Hallberg, NOAA GFDL

Sim James, National ESPC Office

David McCarren, Office of the Oceanographer of the Navy, and National ESPC Office

Avichal Mehra, NOAA NCEP

James Richman, Florida State University

### Workshop Participants:

Scott Bachman, NCAR

Rainer Bleck, NASA GISS and NOAA ESRL

Frank Bryan, NCAR

Eric Chassignet, Florida State University (remote)

Arun Chawla, NOAA NCEP

Mark Cobb, NAVOCEANO

Darren Engwirda, MIT and NASA GISS

Matthew Harrison, NOAA GFDL

Patrick Hogan, NRL

Carlos Lozano, NOAA NCEP

Joe Metzger, NRL

Steve Penny, University of Maryland / NOAA NCEP

Jay Shriver, NRL

Hendrik Tolman, NOAA NWS/OSTI

Alan Wallcraft, NRL

Aijun Zhang, NOAA/NOS

Lianyuan Zheng, NOAA/NOS

### Participating Program Managers:

Heather Archambault, NOAA OAR/CPO

Dan Eleuterio, Office of Naval Research

Scott Harper, Office of Naval Research

Ming Ji, NOAA NWS

Fred Toepfer, NOAA NWS

**Appendix 1. Working Group Meeting Agenda**

## Arbitrary Lagrangian-Eulerian (ALE) Working Group Meeting

NOAA SSMC2, Silver Spring, Maryland, Room 2358

9-10 May 2017

**9 May**

**Overviews**

|  |  |  |
| --- | --- | --- |
| 8:00-8:30 |  | Check-in, refreshments |
| 8:30-9:00 | Arbic/Mehra | Recap of October workshop, summary of recommendations to develop closer ties between NOAA and Navy modeling efforts |
| 9:00-9:20 | Carman | National ESPC and Inter-agency collaboration |
| 9:20-9:40 | McCarren | Navy perspectives |
| 9:40-10:00 | Tolman/Toepfer | NOAA perspectives |
| 10:00-10:30 |  | Break |

**Nuts and bolts**

|  |  |  |
| --- | --- | --- |
| 10:30-11:00 | Wallcraft/Hallberg/  Mehra/Arbic | What has been done to look at the differences between HYCOM and MOM6 and what are near-term activities |
| 11:00-11:20 | Penny | Ocean modeling and data assimilation needs |
| 11:20-11:40 | Wallcraft | Navy/NRL perspective on requirements for the global ocean, what needs to be done and what resources are needed |
| 11:40-12:00 | Mehra/Chawla/  Lozano | NWS perspective on requirements for the global ocean, what needs to be done and what resources are needed |
| 12:00-1:30 |  | Lunch onsite |
| 1:30-1:50 | Adcroft/Hallberg | GFDL perspective on requirements for the global ocean model, what needs to be done and what resources are needed |
| 1:50-2:10 | Bryan | NCAR perspective on requirements for the global ocean, what needs to be done and what resources are needed |
| 2:10-2:30 | Bleck | Using ALE models for climate research |
| 2:30-2:50 | Arbic | Brief discussion on role of academia in entrainment of computer scientists into the field of ocean model development |
| 2:50-3:20 |  | Break |
| 3:20-5:00 | Arbic/Mehra | Summary of key directions: what do we need to do, to go forward? (technical level) |

**10 May**

|  |  |  |
| --- | --- | --- |
| 8:00 |  | Refreshments |
| 8:30-10:00 | Arbic/Mehra/  Carman | Highlight key points to proceed, clarify details: |
|  |  | What do we need to do to go forward?  Obvious first efforts  Impediments to progress  Who are the users for the merged model?  What requirements beyond the ocean model will impact  the merger?  Coupling to sea ice (CICE vs SIS2, ESMF vs FMS, etc.)  Tides—Who needs tides and who doesn’t?  Input/Output—Formats, native grids or interpolated netcdf?  Data Assimilation—Forecast model needs to include DA and the ability to generate restart files  Resources—people/computer |
| 10:00-10:30 |  | Break |
| 10:30-12:00 | All | Formulation of a technical plan/proposal |
| 12:00 |  | Lunch and end of meeting |