

ROMSTOOLS User's Guide

Pierrick Penven and Thi-Anh Tan

Institut de Recherche pour le Développement (IRD), 213 rue Lafayette, Paris,
France



July, 2007

Contents

1	Introduction	1
1.1	Installation	1
1.1.1	System requirement	1
1.1.2	Getting the files	1
1.1.3	Extracting the files	2
1.2	Future plans	4
1.3	Warning and bugs	4
2	The ROMS model	6
3	Tutorial : the Southern Benguela example	6
3.1	Getting started	6
3.2	Building the grid	9
3.3	Getting the wind and other surface fluxes	12
3.4	Getting the initial and the lateral boundary conditions	15
3.5	Compiling the model	18
3.5.1	param.h	18
3.5.2	cppdefs.h	18
3.6	Running the model	24
3.7	Long simulations	28
3.8	Getting the results	29
3.8.1	roms_gui	29
3.8.2	Diagnostics	31
4	Tides	32
5	Inter-Annual simulations	33
5.1	Getting the surface forcing data from NCEP	33
5.2	Getting the lateral boundary conditions	35
5.3	Running the model	36
6	Embedding	38
6.1	Introduction	38
6.2	Embedded (child) model preparation	39
6.3	Compiling and running the model	41
7	Biology	42
8	Operational coastal modeling system	43

1 Introduction

This guide presents a series of Matlab routines which could be useful for the pre- and post-processing of oceanic regional ROMS simulations. This guide is just a basic users guide, details of the methods and datasets are described in Penven et al. (2007).

The Regional Ocean Modeling System (ROMS) is a new generation ocean circulation model (Shchepetkin and McWilliams, 2005) that has been specially designed for accurate simulations of regional oceanic systems. The reader is referred to Shchepetkin and McWilliams (2003) and to Shchepetkin and McWilliams (2005) for a complete description of the model. ROMS has been applied for the regional simulation of a variety of different regions of the world oceans (e.g. Blanke et al., 2002; Di Lorenzo et al., 2003; Haidvogel et al., 2000; MacCready et al., 2002; Marchesiello et al., 2003; Penven et al., 2001).

To perform a regional simulation using ROMS, the modeler needs to provide several data files in a specific format: horizontal grid, bottom topography, surface forcing, lateral boundary conditions... He also needs to analyze the model outputs. The tools which are described here have been designed to perform these tasks. The goal is to be able to build a standard regional model configuration in a minimum time.

In the first chapter, the system requirements and the installation process are exposed. A short note on ROMS model is presented in chapter 2. A tutorial on the use of ROMSTOOLS is shown in the third chapter. Tidal simulations, inter-annual simulations, nesting tools, biology and operational regional modeling are presented in chapter 4, 5, 6, 7 and 8.

1.1 Installation

1.1.1 System requirement

This toolbox has been designed for Matlab. It needs at least 2 Gbytes of disk space. It has been tested on several Matlab versions ranging from Matlab6 to Matlab2006a. It has been mostly tested on Linux workstations, but it could be used on any platform if a NetCDF and a LoadDAP Matlab Mex files are provided. The NetCDF Matlab Mex file is needed to read and write into NetCDF files and it can be found at the web location: <http://mexcdf.sourceforge.net/>. The LoadDAP Matlab Mex file is used to download data from OpenDAP servers for inter-annual and forecast simulations. It can be found at the web location: <http://www.opendap.org/download/ml-structs.html>. The Matlab LoadDAP Mex file provides a way to read any OpenDAP-accessible data into Matlab. Note that the LibDAP library must be installed on your system before installing LoadDAP. Details can be found at the web location: <http://www.opendap.org>. MexCDF and LoadDAP mex files are provided for Linux (system FEDORA 32bits: mexcdf and Opendap_tools/FEDORA ; system CENTOS or FEDORA 64bits: mexnc and Opendap_tools/FEDORA_X64), but they are not working on all the platforms.

All the other necessary Matlab toolboxes (i.e. air-sea, mask, netcdf or m_map...) are included in the ROMSTOOLS package. Global datasets, such as topography (Smith and Sandwell, 1997), hydrography (Conkright et al., 2002) or surface fluxes (Da Silva et al., 1994), are also included.

1.1.2 Getting the files

All the necessary compressed tar files (XXX.tar.gz) containing the Matlab programs, several datasets and other toolboxes and softwares needed by ROMSTOOLS are located at:

http://www.brest.ird.fr/Roms_tools/index.html

For the ROMS source code you should download ROMS_AGRIF version V1.1.

1.1.3 Extracting the files

Download all the compressed tar files. Uncompress and untar all the files (gunzip and tar -xvf). You should obtain the following directory tree :

```
Roms_tools
|- Aforc_NCEP
|- Aforc_QuikSCAT
|- air_sea
|- COADS05
|- Compile
|- Diagnostic_tools
|- Documentation
|   |- User_guide
|- Forecast_tools
|- mask
|- mex60
|- mexnc
|   |- tests
|- m_map
|   |- private
|- Nesting_tools
|- netcdf_g77
|- netcdf_ifc
|- netcdf_matlab
|   |- listpick
|   |- ncatt
|   |- ncbrowser
|   |- ncdim
|   |- ncfiles
|   |- ncitem
|   |- ncrec
|   |- nctype
|   |- ncutility
|   |- nivar
|   |- netcdf
|- netcdf_x86_64
|- Ofrc_OGCM
|- Opendap_tools
|   |- FEDORA
|   |- FEDORA_X64
|- Preprocessing_tools
|- Roms_Agrif
|   |- AGRIF_ZOOM
|   |   |- AGRIF_FILES
|   |   |- AGRIF_INC
|   |   |- AGRIF_OBJS
|   |   |- AGRIF_YOURFILES
|   |   |- LIB.clean
|- Run
|   |- DATA
|   |- FORECAST
|   |- ROMS_FILES
|   |- SCRATCH
|   |- TEST_CASES
```

- |– SeaWifs
- |– SST_pathfinder
- |– Tides
- |– Topo
 - |– Matlab
- |– TPX06
- |– TPX07
- |– Visualization_tools
- |– WOA2001
- |– WOA2005

Definition of the different directories :

- Aforc_NCEP : Scripts for the recovery of surface forcing data (based on NCEP reanalysis) for inter-annual simulations.
- Aforc_QuikSCAT : Scripts for the recovery of wind stress from satellite scatterometer data (QuickSCAT).
- COADS05 : Directory of the surface fluxes global monthly climatology at 0.5° resolution (Da Silva et al., 1994).
- Compile : Empty scratch directory for ROMS compilation.
- Diagnostic_tools : A few Matlab scripts for animations and basic statistical analysis.
- Documentation : Location of the ROMSTOOLS user guide.
- Forecast_tools : Scripts for the generation of an operational modeling system
- mask : Land mask edition toolbox developed by A.Y. Shcherbina.
- mex60 : Matlab NetCDF interface for 32 bits Linux architectures.
- mexnc : Matlab NetCDF interface for 64 bits Linux architectures.
- m_map : The Matlab mapping toolbox (<http://www2.ocgy.ubc.ca/~rich/map.html>).
- Nesting_tools : Preprocessing tools used to prepare nested models.
- netcdf_g77 : The NetCDF Fortran library for Linux, compiled using g77 (<http://www.unidata.ucar.edu/packages/netcdf/index.html>).
- netcdf_ifc : The NetCDF Fortran library for Linux, compiled with ifort. The Intel Fortran Compiler (ifort) is available at <http://www.intel.com/software/products/compilers/flin/noncom.htm>.
- netcdf_matlab : The Matlab NetCDF toolbox (http://woodshole.er.usgs.gov/staffpages/cdenham/public_html/MexCDF/nc4ml5.html).
- netcdf_x86_64 : The NetCDF Fortran library for Linux, compiled with ifort on a 64 bits architecture.
- Oforc_OGCM : Scripts for the recovery of initial and lateral boundary conditions from global OGCMs (SODA (Carton et al., 2005) or ECCO (Stammer et al., 1999)) for inter-annual simulations.
- Opendap_tools : LoadDAP mexcdf and several scripts to automatically download data over the Internet.
- Preprocessing_tools : Preprocessing Matlab scripts (make_grid.m, make_forcing, etc...).

- Roms_Agrif : ROMS Fortran sources.
- Run : Working directory. This is where the ROMS input files are generated and where the model is running.
- SeaWifs : surface chlorophyll-a climatology based on SeaWifs observations.
- SST_pathfinder : Directory of a higher resolution SST climatology (Reynolds and Smith, 1994) for the thermal correction term.
- Tides : Matlab routines to prepare ROMS tidal simulations. Tidal data are derived from the Oregon State University global models of ocean tides TPXO6 and TPXO7 (Egbert and Erofeeva, 2002): <http://www.oce.orst.edu/research/po/research/tide/global.html>.
- Topo : Location of the global topography dataset at 2' resolution (Smith and Sandwell, 1997). Original data can be found at: http://topex.ucsd.edu/cgi-bin/get_data.cgi
- TPX06 : Directory of the global model of ocean tides TPXO6 (Egbert and Erofeeva, 2002).
- TPX07 : Directory of the global model of ocean tides TPXO7 (Egbert and Erofeeva, 2002).
- Visualization_tools : Matlab scripts for the ROMS visualization graphic user interface.
- WOA2001 : World Ocean Atlas 2001 global dataset (monthly climatology at 1° resolution) (Conkright et al., 2002).
- WOA2005 : World Ocean Atlas 2005 global dataset

1.2 Future plans

- A graphic user interface could be useful for the preprocessing tools.
- There is need for an improvement of the extrapolation and interpolation methods.

1.3 Warning and bugs

- Since Geostrophy is used to obtain the horizontal currents for the lateral boundary conditions, this method should be applied with care close to the Equator. An extrapolation of the currents outside an equatorial band (2°S-2°N) is performed to get an approximation of the equatorial currents.
- On extended grids, the objective analysis used for data extrapolation can be relatively costly in memory and CPU time. The "nearest" Matlab function that is less costly can be used instead. If the computer starts to swap, you should think of reducing the dimension of your model's domain.
- It is sometimes difficult to compile LoadDAP. LibDAP must be installed before installing LoadDAP. Here are a few instructions for the installation of these libraries:
 - Download libDAP and loadDAP tar.gz version at the web location <http://www.opendap.org>
 - To build the libDAP library, follow these steps:
 - * log you as a root
 - * Uncompress and untar the file libdap.tar.gz (gunzip and tar -xvf)
 - * >: cd libdap_directory

- * Type './configure' at the prompt. Some libraries must be installed on your system to successfully run configure and build libDAP library : libcurl (<http://curl.haxx.se/>) and libxml2 (<http://xmlsoft.org/>).

Example:

```
checking for a BSD-compatible install... /usr/bin/install -c
checking whether build environment is sane... yes
checking whether make sets (MAKE)... yes
checking build system type... i686-pc-linux-gnu
checking host system type... i686-pc-linux-gnu
checking for gawk... (cached) mawk
checking for g++... g++
checking for C++ compiler default output file name... a.out
...
config.status: dods-datatypes.h is unchanged
config.status: executing depfiles commands
```

- * Type 'make' to build the library.

Example :

```
make[1]: Entering directory '/home/tropic/tan/soft/libdap-3.6.2'
Making all in gl
make[2]: Entering directory '/home/tropic/tan/soft/libdap-3.6.2/gl'
make all-am
make[3]: Entering directory '/home/tropic/tan/soft/libdap-3.6.2/gl'
...
```

- * Type 'make check' to run the tests. To pass this step you must have DejaGNU framework (GNU FTP mirror list: <http://www.gnu.org/prep/ftp.html>).

Example :

```
make[1]: Entering directory '/home/tropic/tan/soft/libdap-3.6.2/gl'
dejagnu_driver.sh
...
Test Run By tan on Thu Jul 19 11:19:02 2007
Native configuration is i686-pc-linux-gnu
===== das-test tests =====
Running ...
===== das-test Summary =====
===== dds-test tests =====
Running ...
===== dds-test Summary =====
===== expr-test tests =====
Running ...
===== expr-test Summary =====
PASS: dejagnu_driver.sh
=====
All 1 tests passed
=====
make[2]: Leaving directory '/home/tropic/tan/soft/libdap-3.6.2/tests'
make[1]: Leaving directory '/home/tropic/tan/soft/libdap-3.6.2/tests'
```

- * Type 'make install' to install the library. By default the files are installed under /usr/local/lib/. You can specify a different root directory using the following control : 'make install root_directory'.
- * Go to the .bashrc and add
'EXPORT LD_LIBRARY_PATH=\$LD_LIBRARY_PATH : root_directory.'
- The installation of the loadDAP library is done as for libDAP. By default the files are installed under /usr/local/share/.

2 The ROMS model

ROMS solves the primitive equations in an Earth-centered rotating environment, based on the Boussinesq approximation and hydrostatic vertical momentum balance. ROMS is discretized in coastline- and terrain-following curvilinear coordinates. ROMS is a split-explicit, free-surface ocean model, where short time steps are used to advance the surface elevation and barotropic momentum, with a much larger time step used for temperature, salinity, and baroclinic momentum. ROMS employs a special 2-way time-averaging procedure for the barotropic mode, which satisfies the 3D continuity equation (Shchepetkin and McWilliams, 2005). The specially designed predictor-corrector time step algorithm used in ROMS allows a substantial increase in the permissible time-step size.

ROMS has been designed to be optimized on shared memory parallel computer architectures such as the SGI/CRAY Origin 2000. Parallelization is done by two dimensional sub-domains partitioning. Multiple sub-domains can be assigned to each processor in order to optimize the use of processor cache memory. This allow super-linear scaling when performance growth even faster than the number of CPUs.

The third-order, upstream-biased advection scheme implemented in ROMS allows the generation of steep gradients, enhancing the effective resolution of the solution for a given grid size (Shchepetkin and McWilliams, 1998). Explicit lateral viscosity is null everywhere in the model domain except in sponge layers near the open boundaries where it increases smoothly close to the lateral open boundaries.

A non-local, K-profile planetary (KPP) boundary layer scheme (Large, 1994) parameterizes the unresolved physical vertical subgrid-scale processes. If a lateral boundary faces the open ocean, an active, implicit, upstream biased, radiation condition connects the model solution to the surroundings (Marchesiello et al., 2001).

3 Tutorial : the Southern Benguela example

This section presents the essential steps for preparing and running a regional ROMS simulation. This is done following the example of a model of the Southern Benguela at low resolution.

3.1 Getting started

Once the installation has been successful, launch a Matlab session in the directory: ~/Roms_tools/Run. Run the start.m script to set the Matlab paths for this session. The start.m script also makes the difference between 32 bits and 64 bits Linux architectures and adjusts the paths in consequence:

```
> : cd Roms_tools/Run
> : matlab
< M A T L A B >...
>> start
Add the paths of the different toolboxes...
```


Arch : x86_64 - Matlab version : 12
 Use of mex60 and loadlap in 32 bits.
 >>

You are now ready to create a new configuration. It is important to respect the order of the following preprocessing steps: make_grid, make_forcing, make_clim. For all the preprocessing steps, there is only one file to edit : ~/Roms_tools/Run/romstools_param.m . This file contains the necessary parameters for the generation of the ROMS input NetCDF files. The first section in romstools_param.m defines the general parameters, such as title, working directories or file names:

```

%%%%%%%%%%%%%%
%
% 1- General parameters
%
%%%%%%%%%%%%%%
%
% ROMS title names and directories
%
ROMS_title = 'Benguela Test Model';
ROMS_config = 'Benguela';
ROMSTOOLS_dir = '../';
RUN_dir=[ROMSTOOLS_dir,'Run/'];
ROMS_files_dir=[RUN_dir,'ROMS_FILES/'];
%
% ROMS file names (grid, forcing, bulk, climatology, initial)
%
grdname=[ROMS_files_dir,'roms_grd.nc'];
frcname=[ROMS_files_dir,'roms_frc.nc'];
blkname=[ROMS_files_dir,'roms_blk.nc'];
clmname=[ROMS_files_dir,'roms_clm.nc'];
iname=[ROMS_files_dir,'roms_ini.nc'];
oaname =[ROMS_files_dir,'roms_oa.nc']; % oa file : intermediate file not used
% in roms simulations
bryname=[ROMS_files_dir,'roms_bry.nc'];
Zbryname=[ROMS_files_dir,'roms_bry_Z.nc']; % Zbry file: intermediate file not used
% in roms simulations
%
frc_prefix=[ROMS_files_dir,'roms_frc']; % generic bulk forcing file name
% for inter-annual roms simulations (NCEP or GFS)
blk_prefix=[ROMS_files_dir,'roms_blk']; % generic forcing file name
% for inter-annual roms simulations (NCEP or GFS)
%
% Objective analysis decorrelation scale [m]
% (if Roa=0: simple extrapolation method; crude but much less costly)
%
%Roa=300e3;
Roa=0;
%
interp_method = 'cubic'; % Interpolation method: 'linear' or 'cubic'
%
makeplot = 1; % 1: create a few graphics after each preprocessing step
%
%%%%%%%%%%%%%%

```

Variables description:

- `title='Benguela Test Model'` : General title. You can give any name you want for your configuration.
- `ROMS_config = 'Benguela'` : Name of the configuration. This is used for the storage of NCEP or OGCM data for a specific configuration.
- `ROMSTOOLS_dir = './'` : "Roms_tools" directory.
- `RUN_dir=[ROMSTOOLS_dir,'Run/']` : Roms_tools/Run directory. This is where all the work is done.
- `ROMS_files_dir=[RUN_dir,'ROMS_FILES/']` : Roms_tools/Run/ROMS_FILES/ directory. This is where ROMS input NetCDF files are stored.
- `grdname=[ROMS_files_dir,'roms_grd.nc']` : Name of the ROMS input NetCDF grid file. This is where the horizontal grid parameters are stored. In general, we follow the style : XXX_grd.nc.
- `frcname=[ROMS_files_dir,'roms_frc.nc']` : : Name of the ROMS input NetCDF forcing file. This is where the surface forcing variables (such as wind stress) are stored. In general, we follow the style : XXX_frc.nc.
- `blkname=[ROMS_files_dir,'roms_blk.nc']` : Name of the ROMS input NetCDF bulk file. This is where the atmospheric variables used for the bulk parametrization (such as air temperature) are stored. In general, we follow the style : XXX_blk.nc.
- `clmname=[ROMS_files_dir,'roms_clm.nc']` : Name of the ROMS input NetCDF climatology file. This is where ROMS prognostic variables (u,v, temp, salt, ubar, vbar, zeta) for lateral boundary and interior nudging are stored. This file can be large because variables are stored for all the ROMS grid interior points. It is called "a climatology file" because this was the file used in the past for the restoring of the ROMS solution towards an in-situ climatology (such as Levitus for example). In general, we follow the style : XXX_clm.nc.
- `iname=[ROMS_files_dir,'roms_ini.nc']` : Name of the ROMS input NetCDF initial file. This is where ROMS prognostic variables (u,v, temp, salt, ubar, vbar, zeta) are stored for the initial conditions. In general, we follow the style : XXX_ini.nc.
- `oaname=[ROMS_files_dir,'roms_oa.nc']` : Name of an intermediate file which is not used by ROMS. This is equivalent to the climatology file, but on a z vertical coordinate. Firstly, the variables are horizontally interpolated to create a roms_oa.nc file (a OA file). Then, they are vertically interpolated on the ROMS s-coordinate for the climatology file. In general, we follow the style : XXX_oa.nc.
- `bryname=[ROMS_files_dir,'roms_bry.nc']` : Name of the ROMS input NetCDF boundary file. This is an alternative of the climatology file. In this case, variables are only stored for the lateral boundaries. In general, we follow the style : XXX_bry.nc.
- `Zbryname=[ROMS_files_dir,'roms_bry_Z.nc']` : Intermediate file on a z coordinate for the boundary file. In general, we follow the style : XXX_bry_Z.nc.
- `frc_prefix=[ROMS_files_dir,'roms_frc']` : First part of the forcing file names in the case of inter_annual simulations. In this case, a separate file is created for each month. For example, a forcing file based on NCEP for January 2000 is : roms_frc_NCEP_Y2000M1.nc
- `blk_prefix=[ROMS_files_dir,'roms_blk']` : First part of the bulk file names in the case of inter_annual simulations. In this case, a separate file is created for each month. For example, a bulk file based on NCEP for January 2000 is : roms_blk_NCEP_Y2000M1.nc

- Roa=0 : Decorrelation length scale in meters for the objective analysis (300 km is a reasonable value for the employed datasets). If Roa=0, the "nearest" Matlab extrapolation method is used instead of an objective analysis. This is much less costly, but the results might be at a lower quality.
- interp_method = 'cubic' : Horizontal interpolation method used after the objective analysis. It can be linear or cubic.
- makeplot = 1 : Select to generate images after each step of the preprocessing.

3.2 Building the grid

The part of the file romstools_param.m that you should edit is :

```

%%%%%%%%%%
%
% 2-Grid parameters
% used by make_grid.m (and others..)
%
%%%%%%%%%%
%
% Grid dimensions:
%
lonmin = 12.3; % Minimum longitude [degree east]
lonmax = 20.45; % Maximum longitude [degree east]
latmin = -35.5; % Minimum latitude [degree north]
latmax = -26.5; % Maximum latitude [degree north]
%
% Grid resolution [degree]
%
dl = 1/3;
%
% Number of vertical Levels (! should be the same in param.h !)
%
N = 32;
%
% Vertical grid parameters (! should be the same in roms.in !)
%
theta_s = 6.;
theta_b = 0.;
hc = 10.;
%
% Minimum depth at the shore [m] (depends on the resolution,
% rule of thumb: dl=1, hmin=300, dl=1/4, hmin=150, ...)
% This affect the filtering since it works on grad(h)/h.
%
hmin = 75;
%
% Maximum depth at the shore [m] (to prevent the generation
% of too big walls along the coast)
%
hmax_coast = 500;
%
% Topography netcdf file name (ETOPO 2 or any other netcdf file
% in the same format)

```

```

%
topofile = [ROMSTOOLS_dir,'Topo/etopo2.nc'];
%
% Slope parameter (r=grad(h)/h) maximum value for topography smoothing
%
rtarget = 0.25;
%
% Number of pass of a selective filter to reduce the isolated
% seamounts on the deep ocean.
%
n_filter_deep_topo=4;
%
% Number of pass of a single hanning filter at the end of the
% smoothing procedure to ensure that there is no 2DX noise in the
% topography.
%
n_filter_final=2;
%
% GSHSS user defined coastline (see m_map)
% XXX_f.mat Full resolution data
% XXX_h.mat High resolution data
% XXX_i.mat Intermediate resolution data
% XXX_l.mat Low resolution data
% XXX_c.mat Crude resolution data
%
coastfileplot = 'coastline_l.mat';
coastfilemask = 'coastline_l_mask.mat';

```

Variables description:

- lonmin = 12.3 : Western limit of the grid in longitude $[-360^\circ, 360^\circ]$. The grid is rectangular in latitude/longitude.
- lonmax = 20.45 : Eastern limit $[-360^\circ, 360^\circ]$. Should be superior to lonmin.
- latmin = -35.5 : Southern limit of the grid in latitude $[-90^\circ, 90^\circ]$.
- latmax = -26.5 : Northern limit $[-90^\circ, 90^\circ]$. Should be superior to latmin.
- l = 1/3 : Grid longitude resolution in degrees. The latitude spacing is deduced to obtain an isotropic grid using the relation: $d\phi = dl \cos(\phi)$.
- N = 32 : Number of vertical levels. Warning! N has to be also defined in the file : `~/Roms_tools/Run/param.h` before compiling the model.
- theta_s = 6. : Vertical S-coordinate surface stretching parameter. When building the climatology and initial ROMS files, we have to define the vertical grid. Warning! The different vertical grid parameters should be identical in this file and in the ROMS input file (i.e. `~/Roms_tools/Run/roms.in`). This is a serious cause of bug. The effects of theta_s, theta_b, hc, and N can be tested using the Matlab script : `~/Roms_tools/Preprocessing_tools/test_vgrid.m`.
- theta_b = 0. : Vertical S-coordinate bottom stretching parameter.
- hc = 10. : Vertical S-coordinate H_c parameter. It gives approximately the transition depth between the horizontal surface levels and the bottom terrain following levels. It should be inferior to hmin.

- `hmin = 75` : Minimum depth in meters. The model depth is cut at this level to prevent, for example, the occurrence of model grid cells without water. This does not influence the masking routines. At lower resolution, `hmin` should be quite large (for example 150m for $dl=1/2$). Otherwise, since topography smoothing is based on $\frac{\nabla h}{2h}$, the bottom slopes can be totally eroded.
- `hmax_coast = 500` : Maximum depth under the mask. It prevents selected isobaths (here 500 m) to go under the mask. If this is the case, this could be a source of problems for western boundary currents (for example).
- `topofile = [ROMSTOOLS_dir,'Topo/etopo2.nc']` : Default topography file. We are using here `etopo2` (Smith and Sandwell, 1997).
- `rtarget = 0.25` : This variable controls the maximum value of the r -parameter that measures the slope of the sigma layers (Beckmann and Haidvogel, 1993):

$$r = \frac{\nabla h}{2h} = \frac{h_{+1/2} - h_{-1/2}}{h_{+1/2} + h_{-1/2}}$$

To prevent horizontal pressure gradients errors, well known in terrain-following coordinate models (Haney, 1991), realistic topography requires some smoothing. Empirical results have shown that reliable model results are obtained if r does not exceed 0.2.

- `n_filter_deep_topo=4` : Number of pass of a Hanning filter to prevent the occurrence of noise and isolated seamounts on deep regions.
- `n_filter_final=2` : Number of pass of a Hanning filter at the end of the smoothing process to be sure that no noise is present in the topography.
- `coastfileplot = 'coastline_l.mat'` : Binary GSHSS coastal file used by `m_map` for graphical purposes. The letter before ".mat" selects the coastline resolution. f: Full resolution, h: High resolution, i: Intermediate resolution, l: Low resolution c: Crude resolution.
- `coastfilemask = 'coastline_l_mask.mat'` : Binary file used for the coastline in the masking toolbox.

Save `romstools_param.m` and run `make_grid` in the Matlab session :

```
>>
>> make_grid
```

You should obtain in the Matlab session:

Making the grid: `../Run/ROMS_FILES/roms_grd.nc`

Title: Benguela Test Model

Resolution: 1/3 deg

Create the grid file...

`LLm = 23`

`MMm = 31`

Fill the grid file...

Compute the metrics...

Min `dx=30.1583 km` - Max `dx=33.1863 km`

Min dy=30.2091 km - Max dy=33.057 km

Fill the grid file...

Add topography...

ROMS resolution : 31.7 km

Topography data resolution : 3.44 km

Topography resolution halved 4 times

New topography resolution : 54.8 km

Processing coastline_l.mat ...

Do you want to use editmask ? y,[n]

Apply a filter on the Deep Ocean to remove the isolated seamounts :

4 pass of a selective filter.

Apply a selective filter on $\log(h)$ to reduce $\text{grad}(h)/h$:

13 iterations - $r_{\max} = 0.24879$

Smooth the topography a last time to prevent 2DX noise:

2 pass of a hanning smoother.

Write it down...

Do a plot...

>>

You should keep the values of LLM and MMm during the process. They will be necessary for the ROMS parameter file `~/Roms_tools/Run/param.h`. In this test case, $LLm0 = 23$ and $MMm0 = 31$.

During the grid generation process, the question "Do you want to use editmask ? y,[n]" is asked. The default answer is n (for no). If the answer is y (for yes), editmask, the graphic interface developed by A.Y.Shcherbina, will be launched to manually edit the mask (Note that, for the moment, editmask is not working with matlab7 and mexnc). Otherwise the mask is generated from the unfiltered topography data. A procedure prevents the existence of isolated land (or sea) points.

Figure (1) presents the bottom topography obtained with `make_grid.m` for the Southern Benguela example. Note that at this low resolution ($1/3^\circ$), the topography has been strongly smoothed.

3.3 Getting the wind and other surface fluxes

The next step is to create the file containing the different surface fluxes. The part of the file `romstools_param.m` that you should edit is :

```
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 3-Surface forcing parameters
% used by make_forcing.m and by make_bulk.m
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% COADS directory (for climatology runs)
%
coads_dir=[ROMSTOOLS_dir,'COADS05/'];
%
% COADS time (for climatology runs)
%
coads_time=(15:30:345); % days: middle of each month
coads_cycle=360; % repetition of a typical year of 360 days
%
```



Figure 1: Result of make_grid.m for the Benguela example

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% 3.1 Surface forcing parameters
% used by pathfinder_sst.m
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
pathfinder_sst_name=[ROMSTOOLS_dir,...
'SST_pathfinder/climato_pathfinder.nc'];

```

Variables description:

- coads_dir=[ROMSTOOLS_dir,'COADS05/'] : Directory where the global atlas of surface marine data at 1/2° resolution (Da Silva et al., 1994) is located.
- coads_time=(15:30:345) : Time in days for the monthly climatology. It corresponds to the middle of each month. ROMS uses this time to interpolate linearly the forcing variables in time.
- coads_cycle=360 : Duration on which the forcing variables are cycled. Here, for the sake of simplicity, we are running the model on a repeating climatological year of 360 days.
- pathfinder_sst_name=[ROMSTOOLS_dir,SST_pathfinder/climato_pathfinder.nc'] : Directory of the monthly climatology of sea surface temperature from Pathfinder satellite observations (Casey and Cornillon, 1999). This can be used as an alternative of Da Silva et al. (1994) SST.

Save romstools_param.m and run make_forcing in the Matlab session :

```

>>
>> make_forcing

```

You should obtain :

Benguela Test Model

Read in the grid...

Create the forcing file...

Getting tau_x for time index 1

Getting tau_y for time index 1

...

Make a few plots...

>>

This program can take a relatively long time to process all the forcing variables. Figure (2) presents the wind stress vectors and wind stress norm obtained from the global atlas of surface marine data at 1/2° resolution (Da Silva et al., 1994) at 4 different periods of the year. Da Silva et al. (1994) sea surface temperature (SST) is used for the restoring term (dQ_dSST) in the heat flux calculation. To improve the model solution it is possible to use a SST climatology at a finer resolution (9.28 km) (Casey and Cornillon, 1999). To do so, you can run `pathfinder_sst.m` in the Matlab session :

>>

>> `pathfinder_sst`

You should obtain :

... Month index: 1

... Month index: 2

...

>>

For the surface forcing, instead of directly prescribing the fluxes, it is possible to use a bulk formula to generate the surface fluxes from atmospheric variables during the model run. In this case, ROMS needs to be recompiled with the `BULK_FLUX` cpp key defined. To generate the bulk forcing file, you need to run `make_bulk` in the Matlab session :

>>

>> `make_bulk`

You should obtain :

Benguela Test Model

Read in the grid...

Create the bulk forcing file...

Getting sat for time index 1

Getting sat for time index 2

...

Make a few plots...

>>

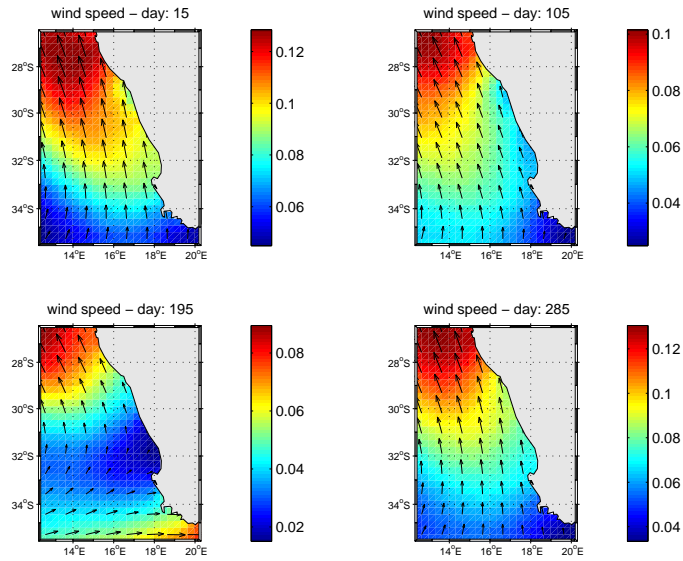


Figure 2: Wind stress[N.m⁻²] obtained using make_forcing.m for the Benguela example.

3.4 Getting the initial and the lateral boundary conditions

The last preprocessing step consists in generating the files containing the necessary informations for the ROMS initial and lateral open boundaries conditions. This script generates two files : the climatology file (XXX_clm.nc) which gives the lateral boundary conditions, and the initial conditions file (XXX_ini.nc). The part which should be edited by the user in the file romstools_param.m is:

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% 4-Open boundaries and initial conditions parameters
% used by make_clim.m, make_biol.m, make_bry.m
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Open boundaries switches (! should be consistent with cppdefs.h !)
%
obc = [1 1 1 1]; % open boundaries (1=open , [S E N W])
%
% Level of reference for geostrophy calculation
%
zref = -1000;
%
% Switches for selecting what to process in make_clim (1=ON)
% (and also in make_OGCM.m and make_OGCM_frst.m)
makeini=1; %1: process initial data
makeclim=1; %1: process lateral boundary data
makebry=0; %1: process boundary data
%
makeoa=1; %1: process oa data (intermediate file)
makeZbry=0; %1: process data in Z coordinate
%
```

```

insitu2pot=1; %1: convert in-situ temperature into potential temperature
%
% Day of initialization for climatology experiments (=0 : 1st January 0h)
%
tini=0;
%
% World Ocean Atlas directory (WOA2001 or WOA2005)
%
woa_dir=[ROMSTOOLS_dir,'WOA2005/'];
%
% Surface chlorophyll seasonal climatology (WOA2001 or SeaWifs)
%
chla_dir=[ROMSTOOLS_dir,'SeaWifs/'];
%
% Set times and cycles for the boundary conditions:
% monthly climatology
%
woa_time=(15:30:345); % days: middle of each month
woa_cycle=360; % repetition of a typical year of 360 days
%
```

Variables description:

- `obc=[1 1 1 1]` : Switches to open (1=open) or close (0=wall) the lateral boundaries [South East North West]. This is used for the application of mass enforcement. Be aware, this should be compatible with the open boundary CPP-switches in the file `~/Roms_tools/Run/cppdefs.h`.
- `zref=-1000` : Depth [meters] of the level of no motion for the geostrophic velocities calculation.
- `makeini=1` : Switch to define if the initial file (`roms_ini.nc`) is generated. Should be 1.
- `makeclim=1` : Switch to define if the climatology (lateral boundary conditions) file (`roms_clm.nc`) is generated. Should be 1.
- `makeoa=1` : Switch to define if the OA (objective analysis; `roms_oa.nc`) file is generated. This should be 1. The OA files are intermediate files where hydrographic data are stored on a ROMS horizontal grid but on a z vertical grid. The transformation into S-coordinate is done later. This file is not used by ROMS.
- `makebry=1` : Switch to define if the boundary file (`roms_bry.nc`) is generated. Used only with `make_bry`.
- `makeZbry=1` : Switch to define if the boundary intermediate file on a z coordinate (`roms_bry_Z.nc`) is generated. Used only with `make_bry`.
- `insitu2pot=1` : Switch defined if it is in-situ temperature that is provided. In this case, in-situ temperature is converted into potential temperature.
- `tini=0` : Day of initialization in climatology experiments (15 = January 15).
- `woa_dir=[ROMSTOOLS_dir,'WOA2005/']` : Directory where the World Ocean Atlas 2005 climatology (Conkright et al., 2002) is located. The World Ocean Atlas 2001 climatology can also be used.
- `chla_dir=[ROMSTOOLS_dir,'SeaWifs/']` : Directory of the surface chlorophyll seasonal climatology.
- `woa_time=(15:30:345)` : Time in days for the WOA monthly climatology. It corresponds to the middle of each month. ROMS uses this variable to interpolate linearly the climatology variables in time.

- `woa_cycle=360` : Duration on which the climatology variables are cycled. Here, for the sake of simplicity, we are running the model on a repeating climatological year of 360 days.

Save `romstools_param.m` and run `make_clim` in the Matlab session :

```
>>
>> make_clim
```

You should obtain :

Making the clim: `../Run/ROMS_FILES/roms_clm.nc`

Title: Benguela Test Model

Read in the grid...

Create the climatology file...

Creating the file : `../Run/ROMS_FILES/roms_clm.nc`

...

Make a few plots...

```
>>
```

This program can also take quite a long time to run. Figure (3) presents 4 different sections of temperature for the initial condition file for the Benguela example. The sections are in the X-direction (East-West), the first section is for the Southern part of the domain and the last one is for the Northern part of the domain.

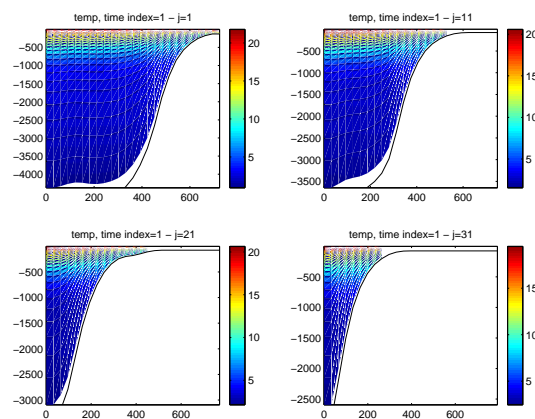


Figure 3: Result of `make_clim.m` for the Benguela example

An alternative of using a climatology file is to create a boundary file. In this case, only boundary values are stored. The cpp key `FRC_BRY` should be defined and ROMS recompiled. Run `make_bry` in the Matlab session :

```
>>
>> make_bry
```

You should obtain :

Making the file: `../Run/ROMS_FILES/roms_bry.nc`

Title: Benguela Test Model

Read in the grid...

...

3.5 Compiling the model

Once all the netcdf data files are ready (i.e. XXX_grd.nc, XXX_frc.nc, XXX_ini.nc, and XXX_clm.nc), we can prepare ROMS for compilation. All is done in the ~/Roms_tools/Run/ directory.

3.5.1 param.h

Edit the file ~/Roms_tools/Run/param.h. The line which needs to be changed is:

```
# elif defined BENGUELA
    parameter (LLm0=23, MMm0=31, N=32) ! < -- Southern Benguela Test Case
# else
```

These are the values of the model grid size: LLm0 points in the X direction, MMm0 points in the Y direction and N vertical levels. LLm0 and MMm0 are given by running make_grid.m, and N is defined in romstools_param.m.

3.5.2 cppdefs.h

The second file to edit is ~/Roms_tools/Run/cppdefs.h. This file defines the CPP keys that are used by the C-preprocessor when compiling ROMS. The C-preprocessor selects the different parts of the Fortran code which needs to be compiled depending on the defined CPP options. These options are separated in two parts (the basic option keys and the advanced options keys) in cppdefs.h.

Definitions of the CCP keys in cppdefs.h:

- BASIN : Must be defined for running the Basin Example.
- CANYON_A : Must be defined for running the Canyon_A Example.
- CANYON_B : Must be defined for running the Canyon_B Example.
- GRAV_ADJ : Must be defined for running the Gravitational Adjustment Example.
- INNERSHELF : Must be defined for running the Inner Shelf Example.
- OVERFLOW : Must be defined for running the Gravitational/Overflow Example.
- SEAMOUNT : Must be defined for running the Seamount Example.
- SHELFROUNT : Must be defined for running the Shelf Front Example.
- SOLITON : Must be defined for running the Equatorial Rossby Wave Example.
- UPWELLING : Must be defined for running the Upwelling Example.
- VORTEX : Must be defined for running the Baroclinic Vortex Example.
- REGIONAL : Must be defined if running realistic regional simulations.

BASIC OPTIONS

/* Configuration Name */

- BENGUELA : Configuration Name, this is used in param.h.

/* Parallelization */

- OPENMP : Activate the Open-MP parallelization protocol.
- MPI : Activate the MPI parallelization protocol.

/* Embedding */

- AGRIF : Activate the nesting capabilities

/* Open Boundary Conditions */

- TIDES : Force tidal currents at the lateral boundaries.
- OBC_EAST : Open eastern boundary (should be consistent with make_clim.m).
- OBC_WEST : Open western boundary (should be consistent with make_clim.m).
- OBC_NORTH : Open northern boundary (should be consistent with make_clim.m).
- OBC_SOUTH : Open southern boundary (should be consistent with make_clim.m).

/* Embedding conditions */

- AGRIF_OBC_EAST : Open eastern boundary for the child grids.
- AGRIF_OBC_WEST : Open western boundary for the child grids.
- AGRIF_OBC_NORTH : Open northern boundary for the child grids.
- AGRIF_OBC_SOUTH : Open southern boundary for the child grids.

/* Applications */

- BIOLOGY : Activate the biogeochemical module.
- FLOATS : Activate floats.
- STATIONS : Store model outputs for each time step at different station locations.
- PASSIVE_TRACER : Add a passive tracer.
- SEDIMENT : Activate the sediment module.
- BBL : Activate the bottom boundary layer module.

MORE ADVANCED OPTIONS

/* Model dynamics */

- SOLVE3D : Define if solving 3D primitive equations.
- UV_COR : Activate Coriolis terms.
- UV_ADV : Activate advection terms.
- SSH_TIDES : Define for processing sea surface elevation tidal data at the model boundaries.
- UV_TIDES : Define for processing ocean current tidal data at the model boundaries.
- TIDERAMP : Apply a ramping of the tidal current, (in general 2 days) at initialization. Warning! This should be off when restarting the model.

/* Grid configuration */

- CURVGRID : Activate curvilinear coordinate grid option.
- SPHERICAL : Activate longitude/latitude grid positioning.
- MASKING : Activate land masking in the domain.

/* Input/Output and Diagnostics */

- AVERAGES : Define if writing out time-averaged data.
- AVERAGES_K : Define if writing out time-averaged vertical mixing.
- DIAGNOSTICS_TS : Define if writing out tendency terms for the tracer equations.
- DIAGNOSTICS_UV : Define if writing out tendency terms for the momentum equations.

/* Equation of State */

- SALINITY : Define if using salinity.
- NONLIN_EOS : Activate the nonlinear equation of state.
- SPLIT_EOS : Activate the split of the nonlinear equation of state in a adiabatic part and a compressible part for the reduction of pressure gradient errors (Shchepetkin and McWilliams, 2003).

/* Surface Forcing */

- QCORRECTION : Activate net heat flux correction.
- SFLX_CORR : Activate freshwater flux correction.
- DIURNAL_SRFLUX : Activate diurnal modulation of the short wave radiation flux.
- BULK_FLUX : Activate the bulk parametrization.
- BULK_EP: Activate the bulk parametrization for salinity fluxes.

/* Lateral Forcing */

- SPONGE : Activate areas of enhanced viscosity/diffusion close to the lateral open boundaries.

- CLIMATOLOGY : Activate processing of climatology data.
- ZCLIMATOLOGY : Activate processing of sea surface height climatology.
- M2CLIMATOLOGY : Activate processing of barotropic velocities climatology.
- M3CLIMATOLOGY: Activate processing of baroclinic velocities climatology.
- TCLIMATOLOGY : Activate processing of tracer climatology.
- ZNUDGING : Activate open boundary passive/active term + nudging layer for zeta.
- M2NUDGING : Activate open boundary passive/active term + nudging layer for ubar and vbar.
- M3NUDGING : Activate open boundary passive/active term + nudging layer for u and v.
- TNUDGING : Activate open boundary passive/active term + nudging layer for tracers.
- ROBUST_DIAG : Activate strong tracer nudging in the interior for diagnostic simulations.
- FRC_BRY : Activate direct boundary forcing (roms_bry.nc).
- Z_FRC_BRY : Activate boundary forcing for zeta.
- M2_FRC_BRY : Activate boundary forcing for ubar and vbar.
- M3_FRC_BRY : Activate boundary forcing for u and v.
- T_FRC_BRY : Activate boundary forcing for tracers.

/* Bottom Forcing */

- ANA_BSFLUX : Define if using analytical bottom salinity flux.
- ANA_BTFLUX : Define if using analytical bottom temperature flux.

/* Point Sources - Rivers */

- PSOURCE : Define if using point sources (rivers).
- ANA_PSOURCE : Define if using analytical vertical profiles for the point sources (using fluxes defined in roms.in).

/* Lateral Mixing */

- UV_VIS2 : Activate Laplacian horizontal mixing of momentum.
- MIX_GP_UV : Activate mixing on geopotential (constant Z) surfaces.
- SMAGORINSKY : Activate Smagorinsky parametrization for horizontal mixing.
- TS_DIF2: Activate Laplacian horizontal mixing of tracers.
- MIX_GP_TS : Activate mixing on geopotential (constant Z) surfaces.
- CLIMAT_TS_MIXH : Activate horizontal mixing of T-Tclim instead of T for the tracers.

/* Vertical Mixing */

- BODYFORCE : Define if applying surface and bottom stresses as bodyforces.
- BVF_MIXING : Activate a simple mixing scheme based on the Brunt-Väisälä frequency.

- LMD_MIXING : Activate Large/McWilliams/Doney mixing (LMD-KPP closure).
- LMD_SKPP : Activate surface boundary layer KPP mixing (LMD-KPP closure).
- LMD_BKPP : Activate bottom boundary layer KPP mixing (LMD-KPP closure).
- LMD_RIMIX : Activate shear instability interior mixing (LMD-KPP closure).
- LMD_CONVEC : Activate convection interior mixing (LMD-KPP closure).
- LMD_DDMIX : Activate double diffusion interior mixing (LMD-KPP closure).
- LMD_NONLOCAL : Activate nonlocal transport (LMD-KPP closure).

/* Open Boundary Conditions */

- OBC_M2FLATHER : Activate Flather open boundary conditions for ubar and vbar.
- OBC_M2CHARACT : Activate open boundary conditions based on characteristic methods for ubar and vbar.
- OBC_VOLCONS : Activate mass conservation enforcement at open boundaries.
- OBC_M2ORLANSKI : Activate 2D radiation open boundary conditions for ubar and vbar.
- OBC_M2SPECIFIED : Activate specified open boundary conditions for ubar and vbar.
- OBC_M3ORLANSKI : Activate 2D radiation open boundary conditions for u and v.
- OBC_M3CHARACT : Activate open boundary conditions based on characteristic methods for u and v.
- OBC_M3SPECIFIED : Activate specified open boundary conditions for u and v.
- OBC_TORLANSKI : Activate 2D radiation open boundary conditions for tracers.
- OBC_TUPWIND : Activate upwind open boundary conditions for tracers.
- OBC_TSPECIFIED : Activate specified open boundary conditions for tracers.

/* Embedding conditions */

- AGRIF_STORE_BAROT_CHILD : Store ubar and vbar during the parent step for the child boundary conditions (Nesting).
- AGRIF_FLUX_BC : Apply parent/child barotropic boundary conditions as fluxes (Nesting).
- AGRIF_POLY_DUAVG : Apply a third order polynomial temporal interpolation for parent/child coupling of DU_avg1 and DU_avg2 (Nesting).
- AGRIF_LOCAL_VOLCONS : Enforce parent-child mass conservation (Nesting).
- AGRIF_OBC_M2FLATHER : Activate Flather open boundary conditions for ubar and vbar for the child model (Nesting).
- AGRIF_OBC_M2ORLANSKI : Activate 2D radiation open boundary conditions for ubar and vbar for the child model (Nesting).
- AGRIF_OBC_M2SPECIFIED : Activate specified open boundary conditions for ubar and vbar for the child model (Nesting).
- AGRIF_OBC_M2CHARACT : Activate open boundary conditions based on characteristic methods for ubar and vbar for the child model (Nesting).

- AGRIF_OBC_M3ORLANSKI : Activate 2D radiation open boundary conditions for u and v for the child model (Nesting).
- AGRIF_OBC_M3SPECIFIED : Activate specified open boundary conditions for u and v for the child model (Nesting).
- AGRIF_OBC_M3CHARACT : Activate open boundary conditions based on characteristic methods for u and v for the child model (Nesting).
- AGRIF_OBC_TORLANSKI : Activate 2D radiation open boundary conditions for tracers for the child model (Nesting).
- AGRIF_OBC_TUPWIND : Activate upwind open boundary conditions for tracers for the child model (Nesting).
- AGRIF_OBC_TSPECIFIED : Activate specified open boundary conditions for tracers for the child model (Nesting).

/* Applications */

/* Biology */

- BIO_NChIPZD : Select a 5 components (Nitrate, Chlorophyll, Phytoplankton, Zooplankton, Detritus) biogeochemical model.
- BIO_N2ChIPZD2 : Select a 7 components (Nitrate, Ammonium, Chlorophyll, Phytoplankton, Zooplankton, Small Detritus, Large Detritus) biogeochemical model.
- BIO_N2P2Z2D2 : Select a 8 components (Nitrate, Ammonium, Small Phytoplankton, Large Phytoplankton, Small Zooplankton, Large Zooplankton, Small Detritus, Large Detritus) biogeochemical model.
- DIAGNOSTICS_BIO : Define if writing out fluxes between the biological components.

/* Floats */

- FLOATS_GLOBAL_ATTRIBUTES : Write out global attributes for the floats.
- IBM : Add a fish behavior to the floats (Individual Based Model).
- RANDOM_WALK : Add a random walk for the floats dispersion.
- DIEL_MIGRATION : Add a vertical daily migration to the floats.
- RANDOM_VERTICAL : Add a random walk for the floats depending on the vertical mixing.

/* Stations */

- ALL_SIGMA : Write out all vertical levels in the stations file.

ROMS can be compiled by running the UNIX tcsh script `~/Roms_tools/Run/jobcomp`. Jobcomp should be able to recognize your system. It has been tested on Linux, IBM, Sun and Compaq systems. On Linux PCs, the default compiler is the GNU g77, but it is possible to uncomment specific lines in jobcomp to use g95 or ifort. The latter is mandatory when using AGRIF and/or OPEN_MP. When changing the compiler you should provide a corresponding NetCDF library. Once the compilation is done, you should obtain a new executable (roms) in the `~/Roms_tools/Run` directory. ROMS should be recompiled each time param.h or cppdefs.h are changed.

3.6 Running the model

Edit the input parameter file: `~/Roms_tools/Run/roms.in`. The vertical grid parameters (THETA_S, THETA_B, HC) should be identical to the ones in `romstools_param.m`. Otherwise, the other default values should not be changed. The definition of all the input variables is given at the start of each ROMS simulation. To run the model, type in directory `~/Roms_tools/Run/` : `./roms roms.in`. On the screen, you should check the `Cu_max` parameter: if it is greater than 1 you are violating the CFL criterion. In this case, you should reduce the time step.

Example of model run:

```
> : ./roms roms.in
```

You should obtain :

Southern Benguela
480 ntimes Total number of timesteps for 3D equations.
5400.00 dt Timestep [sec] for 3D equations
60 ndtfast Number of 2D timesteps within each 3D step.
1 ninfo Number of timesteps between runtime diagnostics.

6.000E+00 theta_s S-coordinate surface control parameter.
0.000E+00 theta_b S-coordinate bottom control parameter.
1.000E+01 Tcline S-coordinate surface/bottom layer width used in
vertical coordinate stretching, meters.
Grid File: ROMS_FILES/roms_grd.nc
Forcing Data File: ROMS_FILES/roms_frc.nc
Bulk Data File: ROMS_FILES/roms_blk.nc
Climatology File: ROMS_FILES/roms_clm.nc
Initial State File: ROMS_FILES/roms_ini.nc Record: 1
Restart File: ROMS_FILES/roms_rst.nc nrst = 480 rec/file: -1
History File: ROMS_FILES/roms_his.nc Create new: T nwrt = 480 rec/file = 0
1 ntsavg Starting timestep for the accumulation of output
time-averaged data.
48 navg Number of timesteps between writing of time-averaged
data into averages file.
Averages File: ROMS_FILES/roms_avg.nc rec/file = 0

Fields to be saved in history file: (T/F)
T write zeta free-surface.
F write UBAR 2D U-momentum component.
F write VBAR 2D V-momentum component.
F write U 3D U-momentum component.
F write V 3D V-momentum component.
F write T(1) Tracer of index 1.
F write T(2) Tracer of index 2.

F write RHO Density anomaly.
F write Omega Omega vertical velocity.
F write W True vertical velocity.
F write Akv Vertical viscosity.
F write Akt Vertical diffusivity for temperature.
F write Aks Vertical diffusivity for salinity.
F write Hbl Depth of KPP-model boundary layer.
F write Bostr Bottom Stress.

Fields to be saved in averages file: (T/F)

T write zeta free-surface.

T write UBAR 2D U-momentum component.

T write VBAR 2D V-momentum component.

T write U 3D U-momentum component.

T write V 3D V-momentum component.

T write T(1) Tracer of index 1.

T write T(2) Tracer of index 2.

F write RHO Density anomaly

T write Omega Omega vertical velocity.

T write W True vertical velocity.

F write Akv Vertical viscosity

T write Akt Vertical diffusivity for temperature.

F write Aks Vertical diffusivity for salinity.

T write Hbl Depth of KPP-model boundary layer

T write Bostr Bottom Stress.

1025.0000 rho0 Boussinesq approximation mean density, kg/m3.

0.000E+00 visc2 Horizontal Laplacian mixing coefficient [m2/s]
for momentum.

0.000E+00 tnu2(1) Horizontal Laplacian mixing coefficient (m2/s)
for tracer 1.

0.000E+00 tnu2(2) Horizontal Laplacian mixing coefficient (m2/s)
for tracer 2.

0.000E+00 rdrg Linear bottom drag coefficient (m/si).

0.000E+00 rdrg2 Quadratic bottom drag coefficient.

1.000E-02 Zob Bottom roughness for logarithmic law (m).

1.000E-04 Cdb_min Minimum bottom drag coefficient.

1.000E-01 Cdb_max Maximum bottom drag coefficient.

1.00 gamma2 Slipperiness parameter: free-slip +1, or no-slip -1.

1.00E+05 x_sponge Thickness of sponge and/or nudging layer (m)

800.00 v_sponge Viscosity in sponge layer (m2/s)

1.157E-05 tauT_in Nudging coefficients [sec⁻¹]

3.215E-08 tauT_out Nudging coefficients [sec⁻¹]

1.157E-06 tauM_in Nudging coefficients [sec⁻¹]

3.215E-08 tauM_out Nudging coefficients [sec⁻¹]

Activated C-preprocessing Options:

REGIONAL
 BENGUELA
 OBC_EAST
 OBC_WEST
 OBC_NORTH
 OBC_SOUTH
 SOLVE3D
 UV_COR
 UV_ADV
 CURVGRID
 SPHERICAL
 MASKING
 AVERAGES
 AVERAGES_K

SALINITY
 NONLIN_EOS
 SPLIT_EOS
 BULK_FLUX
 BULK_EP
 SPONGE
 CLIMATOLOGY
 ZCLIMATOLOGY
 M2CLIMATOLOGY
 M3CLIMATOLOGY
 TCLIMATOLOGY
 ZNUDGING
 M2NUDGING
 M3NUDGING
 TNUDGING
 ANA_BSFLUX
 ANA_BTFLUX
 UV_VIS2
 MIX_GP_UV
 TS_DIF2
 MIX_GP_TS
 CLIMAT_TS_MIXH
 LMD_MIXING
 LMD_SKPP
 LMD_BKPP
 LMD_RIMIX
 LMD_CONVEC
 OBC_M2FLATHER
 OBC_M3ORLANSKI
 OBC_TORLANSKI
 M2FILTER_COSINE

Linux 2.6.9-42.0.3.ELsmp x86_64
 NUMBER OF THREADS: 1 BLOCKING: 1 x 1.

Spherical grid detected.

hmin hmax grdmin grdmax Cu_min Cu_max
 75.000000 4803.032721 .301836927E+05 .331215714E+05 0.12176008 0.91533005
 volume=9.523986093261087500000E+14 open_cross=6.104836888312444686890E+09

Vertical S-coordinate System:

level S-coord Cs-curve at_hmin over_slope at_hmax

32 0.0000000 0.0000000 0.000 0.000 0.000
 31 -0.0312500 -0.0009350 -0.373 -2.584 -4.794
 30 -0.0625000 -0.0019030 -0.749 -5.247 -9.746
 29 -0.0937500 -0.0029380 -1.128 -8.074 -15.019
 28 -0.1250000 -0.0040767 -1.515 -11.152 -20.790
 27 -0.1562500 -0.0053591 -1.911 -14.580 -27.249
 26 -0.1875000 -0.0068304 -2.319 -18.466 -34.613
 25 -0.2187500 -0.0085426 -2.743 -22.938 -43.132
 24 -0.2500000 -0.0105560 -3.186 -28.141 -53.095

23 -0.2812500 -0.0129416 -3.654 -34.248 -64.842
 22 -0.3125000 -0.0157835 -4.151 -41.463 -78.776
 21 -0.3437500 -0.0191819 -4.684 -50.031 -95.377
 20 -0.3750000 -0.0232566 -5.262 -60.241 -115.220
 19 -0.4062500 -0.0281514 -5.892 -72.443 -138.993
 18 -0.4375000 -0.0340388 -6.588 -87.056 -167.524
 17 -0.4687500 -0.0411263 -7.361 -104.584 -201.807
 16 -0.5000000 -0.0496640 -8.228 -125.635 -243.041
 15 -0.5312500 -0.0599527 -9.209 -150.939 -292.668
 14 -0.5625000 -0.0723554 -10.328 -181.377 -352.427
 13 -0.5937500 -0.0873092 -11.613 -218.013 -424.414
 12 -0.6250000 -0.1053416 -13.097 -262.126 -511.156
 11 -0.6562500 -0.1270882 -14.823 -315.262 -615.700
 10 -0.6875000 -0.1533158 -16.841 -379.282 -741.723
 9 -0.7187500 -0.1849493 -19.209 -456.432 -893.656
 8 -0.7500000 -0.2231040 -22.002 -549.423 -1076.845
 7 -0.7812500 -0.2691252 -25.306 -661.522 -1297.738
 6 -0.8125000 -0.3246355 -29.226 -796.670 -1564.114
 5 -0.8437500 -0.3915923 -33.891 -959.622 -1885.352
 4 -0.8750000 -0.4723564 -39.453 -1156.112 -2272.770
 3 -0.9062500 -0.5697755 -46.098 -1393.057 -2740.015
 2 -0.9375000 -0.6872846 -54.048 -1678.800 -3303.552
 1 -0.9687500 -0.8290268 -63.574 -2023.407 -3983.240
 0 -1.0000000 -1.0000000 -75.000 -2439.016 -4803.033

Time splitting: ndtfast = 60 nfast = 89

Maximum grid stiffness ratios: rx0 = 0.2353349875 rx1 = 2.5672736953

GET_INITIAL - Processing data for time = 0.000 record = 1

GET_TCLIMA - Read climatology of tracer 1 for time = 345.0

GET_TCLIMA - Read climatology of tracer 1 for time = 15.00

GET_TCLIMA - Read climatology of tracer 2 for time = 345.0

GET_TCLIMA - Read climatology of tracer 2 for time = 15.00

GET_UCLIMA - Read momentum climatology for time = 345.0

GET_UCLIMA - Read momentum climatology for time = 15.00

GET_SSH - Read SSH climatology for time = 345.0

GET_SSH - Read SSH climatology for time = 15.00

GET_SMFLUX - Read surface momentum stresses for time = 345.0

GET_SMFLUX - Read surface momentum stresses for time = 15.00

GET_BULK - Read fields for bulk formula for time = 345.0

GET_BULK - Read fields for bulk formula for time = 15.00

DEF_HIS/AVG - Created new netCDF file 'ROMS_FILES/roms_his.nc'.

WRT_GRID - wrote grid data into file 'ROMS_FILES/roms_his.nc'.

WRT_HIS - wrote history fields into time record = 1 / 1

MAIN: started time-stepping.

STEP time[DAYS] KINETIC_ENRG POTEN_ENRG TOTAL_ENRG NET_VOLUME trd

0 0.00000 0.000000000E+00 2.1475858E+01 2.1475858E+01 9.5239861E+14 0

1 0.06250 1.306369099E-04 2.1476230E+01 2.1476361E+01 9.5239208E+14 0

...

3.7 Long simulations

In many studies, there is a need for long simulations: to reach the spin-up of the solution and/or to obtain statistical equilibriums. For regional models, 10 years appears to be a reasonable model simulation length. In this case, to prevent the generation of large output files, the strategy is to relaunch the model every simulated month. This is done by the UNIX csh script: `run_roms.csh`. Warning! the ROMS input file use for long simulations is `roms_inter.in`. It should be edited accordingly.

1. It gets the grid, the forcing, the initial and the boundary files.
2. It runs the model for 1 month.
3. It stores the output files in a specific form: `roms_avg_Y4M3.nc` (for the ROMS averaged output of March of year 4).
4. It replaces the initial file by the restart file (`roms_rst.nc`) which as been generated at the end of the month.
5. It relaunch the model for next month.

Part to edit in `run_roms.csh`:

```
set MODEL=roms
set SCRATCHDIR='pwd'/SCRATCH
set INPUTDIR='pwd'
set MSSDIR='pwd'/ROMS_FILES
set MSSOUT='pwd'/ROMS_FILES
set CODFILE=roms
set AGRIF_FILE=AGRIF_FixedGrids.in
#
# Model time step [seconds]
#
set DT=5400
#
# Number of days per month
#
set NDAYS = 30
#
# number total of grid levels
#
set NLEVEL=1
#
# Time Schedule - TIME_SCHED=0 -> yearly files
# TIME_SCHED=1 -> monthly files
#
set TIME_SCHED=1
#
set NY_START=1
set NY_END=10
set NM_START=1
set NM_END=12
```

Variables definitions:

- MODEL=roms : Name used for the input files. For example roms_grd.nc.
- SCRATCHDIR='pwd'/SCRATCH : Scratch directory where the model is run
- INPUTDIR='pwd' : Input directory where the roms_inter.in input file is.
- MSSDIR='pwd'/ROMS_FILES : Directory where the roms input NetCDF files (roms_grd.nc, roms_frc.nc, ...) are stored.
- MSSOUT='pwd'/ROMS_FILES : Directory where the roms output NetCDF files (roms_his.nc, roms_avg.nc, ...) are stored.
- CODFILE=roms : ROMS executable.
- AGRIF_FILE=AGRIF_FixedGrids.in : AGRIF input file which defines the position of child grids when using embedding.
- DT=5400 : Model time step in seconds.
- NDAYS = 30 : Number of days in 1 month.
- NLEVEL=1 : Total number of model grids (no AGRIF: NLEVEL=1).
- NY_START=1 : Starting year.
- NY_END=10 : Ending Year.
- NM_START=1 : Starting month.
- NM_END=12 : Ending month.

To run a ROMS long simulation in batch mode on a Linux workstation:

```
> : nohup ./run_roms.csh > exp1.out &
```

To check the execution of your model, type in the directory ~/Roms_Tools/Run :

```
>: more exp1.out
```

3.8 Getting the results

3.8.1 roms_gui

Once the model has run, or during the simulation, it is possible to visualize the model outputs using a Matlab graphic user interface : roms_gui. Launch roms_gui in the Matlab session (in the ~/Roms_tools/Run/ directory):

```
>>
>> roms_gui
```

A window pops up, asking for a ROMS history NetCDF file (Figure 4). You should select roms_his.nc (history file) or roms_avg.nc (average file) and click "open".

The main window appears, variables can be selected to obtain an image such as Figure (5). On the left side, the upper box gives the available ROMS variable names and the lower box presents the variables derived from the ROMS model outputs :

- Ke : Horizontal slice of kinetic energy: $0.5(u^2 + v^2)$.
- Rho : Horizontal slice of density using the non-linear equation of state for seawater of Jackett and McDougall (1995).



Figure 4: Entrance window of roms_gui



Figure 5: roms_gui

- Pot_Rho : Horizontal slice of the potential density.
- Bvf : Horizontal slice of the Brunt-Väisälä frequency: $N^2 = -\frac{g}{\rho} \frac{\partial \rho}{\partial z}$
- Vort : Horizontal slice of vorticity: $\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$.
- Pot_vort : Horizontal slice of the vertical component of Ertel's potential vorticity: $\frac{\partial \lambda}{\partial z} \left[f + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \right]$.
In our case, $\lambda = \rho$.
- Psi : Horizontal slice of stream function: $\nabla^2 \psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$. This routine might be costly since it inverts the Laplacian of the vorticity (using a successive over relaxation solver).
- Speed : Horizontal slice of the ocean currents velocity : $\sqrt{u^2 + v^2}$.
- Transport : Horizontal slice of the transport stream function : $\nabla^2 S_{vd} = \frac{\partial \bar{v}}{\partial x} - \frac{\partial \bar{u}}{\partial y}$.

- Okubo : Horizontal slice of the Okubo-Weiss parameter : $\Lambda^2 = \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 - \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)^2$.
- Chla : Compute a chlorophyll-a from Large and Small phytoplankton concentrations.
- z_SST_1C : Depth of 1°C below SST.
- z_rho_1.25 : Depth of 1.25 kg.m⁻³ below surface density.
- z_max_bvf : Depth of the maximum of the Brunt-Väisälä frequency.
- z_max_dtdz : Depth of the maximum vertical temperature gradient.
- z_20C : Depth of the 20°C isotherm.
- z_15C : Depth of the 15°C isotherm.
- z_sig27 : Depth of the 1027 kg.m⁻³ density layer.
- r_factor : $r = \frac{\nabla h}{2h} = \frac{h_{+1/2} - h_{-1/2}}{h_{+1/2} + h_{-1/2}}$

It is possible to add arrows for the horizontal currents by increasing the "Current vectors spatial step". It is also possible to obtain vertical sections, time series, vertical profiles and Hovmöller diagrams by clicking on the corresponding targets in roms_gui.

3.8.2 Diagnostics

To analyze the long simulations, a few scripts have been added in the directory:
~/Roms_tools/Diagnostic_tools:

- roms_diags.m : Get volume and surface averaged quantities from a ROMS simulation.
- plot_diags.m : Plot the averaged quantities computed by roms_diags.m.
- get_Mmean.m : Get the monthly mean climatology.
- get_Smean.m : Get the seasonal and annual mean climatology from the outputs of get_Mmean.m.
- get_Meddy.m : Get the monthly variance climatology (if the variable nonseasonal = 1, the non-seasonal variance is computed; i.e., the seasonal variation are filtered). It needs that get_Mmean.m and get_Smean.m are run before.
- get_Seddy.m : Get the seasonal and annual RMS from the results of get_Meddy.m.
- roms_anim.m : Create an animation from the monthly history or average files.

Run these scripts in a Matlab session. The obtained mean or eddy files can be visualized with roms_gui.

If you need to create and play ".fli" animations, you should install ppm2fli and xanim on your system. If you have a Linux PC, you can follow these steps:

1. log in as root
2. go to the directory where the file is saved.
3. type : rpm -Uvh ppm2fli-2.1-1.i386.rpm
4. type : rpm -Uvh xanim-2.80.1-12.i386.rpm
5. log out

If you are not using a Linux PC, you should ask your system administrator to install these programs.

4 Tides

Using the method described by Flather (1976), ROMS is able to propagate the different tidal constituents from its lateral boundaries. To do so, define the cpp keys TIDES, SSH_TIDES and UV_TIDES and recompile the model using jobcomp. To work correctly, the model should use the Flather (1976) open boundary radiation scheme (cpp key OBC_M2FLATHER defined). The tidal components are added to the forcing file (XXX_frc.nc) by the Matlab program make_tides.m. Edit the file : ~/Roms_tools/Run/romstools_param.m. The part of the file that you should change is :

```
%%%%%%%%%%
%
% 5-Parameters for tidal forcing
%
%%%%%%%%%%
%
% TPXO file name (TPXO6 or TPXO7)
%
tidename=[ROMSTOOLS_dir,'TPXO6/TPXO6.nc'];
%
% Number of tides component to process
%
Ntides=10;
%
% Chose order from the rank in the TPXO file :
% "M2 S2 N2 K2 K1 O1 P1 Q1 Mf Mm"
% " 1 2 3 4 5 6 7 8 9 10"
%
tidalrank=[1 2 3 4 5 6 7 8 9 10];
%
% Compare with tidegauge observations
%
lon0=18.37;
lat0=-33.91; % Cape Town location
Z0=1; % Mean depth of the tidegauge in Cape Town
```

Variables definitions :

- tidename=[ROMSTOOLS_dir,'TPXO6/TPXO6.nc'] : Location of the netcdf tidal dataset. This file is derived from the Oregon State University global model of ocean tides TPXO.6 (Egbert and Erofeeva, 2002). Data sources can be found at <http://www.oce.orst.edu/po/research/tide/global.html>. It is also possible to use TPXO7.
- Ntides=10 : Number of tidal components to process. Warning! This value should be identical to the value of the parameter Ntides in param.h: "parameter (Ntides=10)".
- tidalrank=[1 2 3 4 5 6 7 8 9 10] : Order to select the different tidal components.
- lon0=18.37;lat0=-33.91;Z0=1 : Location of a tidal gauge to compare the interpolated values with observations.

An important aspect is the definition of time and especially the choice of a time origin. This is defined in `~/Roms_tools/Run/romstools_param.m`:

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% 6-Temporal parameters (used for make_tides, make_NCEP, make_OGCM)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
Yorig = 1900; % reference time for vector time
% in roms initial and forcing files
%
Ymin = 2000; % first forcing year
Ymax = 2000; % last forcing year
Mmin = 1; % first forcing month
Mmax = 3; % last forcing month
%
Dmin = 1; % Day of initialization
Hmin = 0; % Hour of initialization
Min_min = 0; % Minute of initialization
Smin = 0; % Second of initialization
%
SPIN_Long = 0; % SPIN-UP duration in Years

```

The origin of time (Yorig: 1 january of year Yorig) should be kept the same for all the pre-processing and postprocessing steps. Save `romstools_param.m` and run `make_tides` in the Matlab session:

```

>>
>> make_tides

```

You should obtain :

```

Start date for nodal correction : 1-Jan-2000
Reading ROMS grid parameters ...
Tidal components : M2 S2 N2 K2 K1 O1 P1 Q1 Mf Mm
Processing tide : 1 of 10
...

```

5 Inter-Annual simulations

ROMSTOOLS can help to realize inter-annual simulations. In this context, we rely on Ocean Global Circulations Models (OGCM) for the lateral boundary conditions and a global atmospheric reanalysis for the surface forcing (NCEP). To limit the volume of data which needs to be transferred over the Internet, we use Opendap to extract only the necessary subgrids.

5.1 Getting the surface forcing data from NCEP

The Matlab script `make_NCEP.m` is used to obtain the surface forcing data. It downloads the necessary NCEP surface forcing data (Sea Surface Temperature, Wind stress ...) over the Internet, and interpolates them on the model grid. Since `make_NCEP.m` works with the bulk parameterization (i.e. the `BULK_FLUX` and `BULK_EP` cpp keys should be defined in `cppdefs.h`), a surface

forcing NetCDF file and a bulk NetCDF file are generated for each month of your simulation in the directory `~/Roms_tools/Run/ROMSFILES/`. The part of the file `romstools_param.m` that you should change is:

```
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% 7 Parameters for Interannual forcing (SODA, ECCO, NCEP, ...)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Path to Forcing data
%
FORC_DATA_DIR = [RUN_dir,'DATA/'];
%
Download_data = 1; % Get data from the OPENDAP sites
level = 0; % AGRIF level; 0=parent grid
%
% Options for make_NCEP
%
NCEP_dir= [FORC_DATA_DIR,'NCEP_',ROMS_config,'/']; % NCEP data directory
makefr = 1; % 1: Create forcing files
makeblk = 1; % 1: Create bulk files
add_tides = 0; % 1: Add the tides (To be done...)
%
NCEP_version = 1; % NCEP version:
% (1: NCEP/NCAR Reanalysis, 1/1/1948 - present
% 2: NCEP-DOE Reanalysis, 1/1/1979 - 12/31/2001)
%
```

Variables description :

- `FORC_DATA_DIR` : Directory where the different files downloaded over the Internet are stored.
- `Download_data` : Get data from the OPENDAP sites. Should be 1.
- `level` : AGRIF level. The parent grid = 0 and the child grid = 1.
- `NCEP_dir= [FORC_DATA_DIR,'NCEP_',ROMS_config,'/']` : NCEP data directory. This is where NCEP data downloaded over the Internet are stored.
- `makefr` : Switch to define if the forcing file is generated. Should be 1.
- `makeblk` : Switch to define if the bulk file is generated. Should be 1.
- `add_tides` : Switch to define if the tidal forcing is added.
- `NCEP_version` : version of the NCEP reanalysis. 1: NCEP/NCAR Reanalysis, 1/1/1948 - present. 2: NCEP-DOE Reanalysis, 1/1/1979 - 12/31/2001.

Save `romstools_param.m` and run `make_NCEP` in the Matlab session. You should obtain:

```
>> make_NCEP
Add the paths of the different toolboxes
Arch : x86_64 - Matlab version : 2006a
Use of mexnc and loaddap in 64 bits.
Download NCEP data with OPENDAP
```

```

Get NCEP data from 2000 to 2000
Minimum Longitude: 12.3
Maximum Longitude: 20.3
Minimum Latitude: -35.5
Maximum Latitude: -26.3815

```

```

Making output data directory ../Run/DATA/NCEP_Benguela/
Process the first dataset: http://www.cdc.noaa.gov/cgi-bin/nph-nc/Datasets/ncep.reanalysis/surface.gauss/
Create ../Run/DATA/NCEP_Benguela/land.sfc.gauss.nc
Processing year: 2000
Processing month: 1
Get air for year 2000 - month 1
...

```

5.2 Getting the lateral boundary conditions

Initial conditions and lateral boundary conditions can be obtained from several ocean global circulation models (OGCM) such as SODA (Carton et al., 2005) or ECCO (Stammer et al., 1999). The SODA reanalysis is available from 1958 to 2001 and ECCO is available from 1993 until now. The Matlab script `make_OGCM.m` is used to download data over the Internet, and to perform the interpolations on the model grid. A lateral boundary conditions NetCDF file is generated for each month of your simulation in the directory `~/Roms_tools/Run/ROMSFILES/`.

The part of the file `romstools_param.m` that you should change is:

```

%%%%%%%%%%%%%%
%
% Options for make_OGCM
%
%%%%%%%%%%%%%%
OGCM = 'SODA'; % Select the OGCM: SODA(1958-2001), ECCO(1993-2005), ...
OGCM_dir = [FORC_DATA_DIR,OGCM,'_',ROMS_config,'/'];
bry_prefix = [ROMS_files_dir,'roms_bry_',OGCM,'_'];
clm_prefix = [ROMS_files_dir,'roms_clm_',OGCM,'_'];
ini_prefix = [ROMS_files_dir,'roms_ini_',OGCM,'_'];
OGCM_prefix = [OGCM,'_'];
rmdepth = 2;
%
%

```

Variables description :

- `OGCM = 'SODA'` : Name of the OGCM employed (SODA or ECCO).
- `OGCM_dir = [FORC_DATA_DIR,OGCM,'_',ROMS_config,'/']` : OGCM data directory.
- `bry_prefix = [ROMS_files_dir,'roms_bry_',OGCM,'_']` : Left part of the boundary file name.
- `clm_prefix = [ROMS_files_dir,'roms_clm_',OGCM,'_']` : Left part of the climatology file name.
- `ini_prefix = [ROMS_files_dir,'roms_ini_',OGCM,'_']` : Left part of the initial file name.
- `OGCM_prefix = [OGCM,'_']` : Left part of the OGCM file name. This is where OGCM data are stored.

- `rmdepth = 2` : Number of bottom levels to remove. This is useful when there is no valid data at this level. For example, if the depth in the ROMS domain is shallower than the OGCM depth.

Save `romstools_param.m` and run `make_OGCM` in the Matlab session. You should obtain:

```
>> make_OGCM
Add the paths of the different toolboxes
Arch : x86_64 - Matlab version : 2006a
Use of mexnc and loaddap in 64 bits.
Download data...

Get data from Y2000M1 to Y2000M3
Minimum Longitude: 12.3
Maximum Longitude: 20.3
Minimum Latitude: -35.5
Maximum Latitude: -26.3815

Making output data directory ../Run/DATA/SODA_Benguela/
Process the dataset: http://iridl.ldeo.columbia.edu./SOURCES/.CARTON-GIESE/.SODA/.v1p4p3
Processing year: 2000
Processing month: 1
Download SODA for 2000 - 1
...SSH
...U
...
```

5.3 Running the model

Compile the model with `jobcomp` (and with the `cpp` keys `BULK_FLUX` and `BULK_EP` defined) and edit the input parameter file `~/Roms_tools/Run/roms_inter.in` as for the climatology experiments. As for the long simulations, a `csh` script (`run_roms_inter.csh`) manages the handling of input and output files. It also changes the number of time steps so each month has the correct length. This script takes care of leap years. For example Y1996M2 (February 1996) is 29 days long.

Part to edit in `run_roms_inter.csh`:

```
#
set MODEL=roms
set SCRATCHDIR='pwd'/SCRATCH
set INPUTDIR='pwd'
set MSSDIR='pwd'/ROMS_FILES
set MSSOUT='pwd'/ROMS_FILES
set CODFILE=roms
set AGRIF_FILE=AGRIF_FixedGrids.in
#
set BULK_FILES=1
set FORCING_FILES=1
set CLIMATOLOGY_FILES=0
set BOUNDARY_FILES=1
#
# Atmospheric surface forcing dataset (NCEP, GFS,...)
#
set ATMOS=NCEP
#
# Oceanic boundary and initial dataset (SODA, ECCO,...)
```

```

#
set OGCM=SODA
#
# Model time step [seconds]
#
set DT=5400
#
# number total of grid levels (1: No child grid)
#
set NLEVEL=1
#
set NY_START=2000
set NY_END=2000
set NM_START=1
set NM_END=3
#
# Restart file - RSTFLAG=0 -> No Restart
# RSTFLAG=1 -> Restart
#
set RSTFLAG=0
#
# Time Schedule - TIME_SCHED=0 -> yearly files
# TIME_SCHED=1 -> monthly files
#
set TIME_SCHED=1
#
#####

```

Variables definitions:

- MODEL=roms : Name used for the input files. For example roms_grd.nc.
- SCRATCHDIR='pwd'/SCRATCH : Scratch directory where the model is run.
- INPUTDIR='pwd' : Input directory where the roms_inter.in input file is located.
- MSSDIR='pwd'/ROMS_FILES : Directory where the roms input NetCDF files (roms_grd.nc, roms_frc.nc, ...) are stored.
- MSSOUT='pwd'/ROMS_FILES : Directory where the roms output NetCDF files (roms_his.nc, roms_avg.nc, ...) are stored.
- CODFILE=roms : ROMS executable.
- AGRIF_FILE=AGRIF_FixedGrids.in : AGRIF input file which defines the position of child grids when using embedding.
- BULK_FILES=1 : 1 if using bulk NetCDF files (should be 1 for NCEP).
- FORCING_FILES=1 : 1 if using forcing NetCDF files (should be 1 for NCEP).
- CLIMATOLOGY_FILES=0 : 1 if using XXX_clm.nc files. Using a climatology file for each month can take a lot of disc space. It is less costly to use boundary files (XXX_bry.nc).
- BOUNDARY_FILES=1 : 1 if using XXX_bry.nc files.
- ATMOS=NCEP : name of the atmospheric reanalysis. For the moment it is only NCEP.
- OGCM=SODA : name of the OGCM for the boundary conditions. SODA or ECCO.

- DT=5400 : Model time step in seconds.
- NDAYS = 30 : Number of days in 1 month.
- NLEVEL=1 : Total number of model grids (no embedding: NLEVEL=1).
- NY_START=2000 : Starting year.
- NY_END=2000 : Ending Year.
- NM_START=1 : Starting month.
- NM_END=3 : Ending month.
- RSTFLAG=0 : 1 if restarting a simulation
- TIME_SCHED=1 : (obsolete) 0 if using yearly files, 1 if using monthly files. Since make_NCEP and make_OGCM are creating only monthly files, it should be always 1.

As for ROMS long climatology experiments, inter-annual experiments can be run in batch mode:

```
>: nohup ./run_roms_inter.csh > exp1.out &
```

6 Embedding

6.1 Introduction

To address the challenge of bridging the gap between near-shore and offshore dynamics, a nesting capability has been added to ROMS and tested for the California Upwelling System (Penven et al., 2006). The method chosen for embedded gridding takes advantage of the AGRIF (Adaptive Grid Refinement in Fortran) package (Blayo and Debreu, 1999; Debreu, 2000; Debreu and Blayo, 2003; Debreu and Vouland, 2003). AGRIF is a Fortran 95 package for the inclusion of adaptive mesh refinement features within a finite difference numerical model. One of the major advantages of AGRIF in static-grid embedding is the ability to manage an arbitrary number of fixed grids and an arbitrary number of embedding levels.



Figure 6: Temporal coupling between a parent and a child grid for a refinement factor of 3. The coupling is done at the baroclinic time step.

A recursive integration procedure manages the time evolution for the child grids during the time step of the parent grids (Figure 6). In order to preserve the CFL criterion, for a typical coefficient of refinement (say, a factor of 3 for a 5 km resolution grid embedded in a 15 km grid), for each parent time step the child must be advanced using a time step divided by the coefficient of refinement as many time as necessary to reach the time of the parent (Figure (6)). For simple 2-level embedding, the procedure is as follows:

1. Advance the parent grid by one parent time step.
2. Interpolate the relevant parent variables in space and time to get the boundary conditions for the child grid.
3. Advance the child grid by as much child time steps as necessary to reach the new parent model time.
4. Update point by point the parent model by averaging the more accurate values of the child model (in the case of 2-way embedding).

The recursive approach used in AGRIF allows the specification of any number of embedding level.

6.2 Embedded (child) model preparation

To run an embedded model, the user must provide the grid, the surface forcing and the initial conditions. To name the different files, AGRIF employs a specific strategy: if the parent file names are of the form: XXX.nc, the first child names will be of the form: XXX.nc.1, the second: XXX.nc.2, etc... This convention is also applied for the "roms.in" input files.

A graphic user interface (NestGUI) facilitates the generation of the different NetCDF files. Launch nestgui in the Matlab session (in the ~/Roms_tools/Run/ directory):

```
>>
>> nestgui
```

A window pops up, asking for a "PARENT GRID" NetCDF file (Figure 7). In our Benguela test case, you should select ~/Roms_tools/Run/ROMSFILES/roms_grd.nc (grid file) and click "open". The main window appears (Figure 8).



Figure 7: Entrance window of NestGUI

To generate the child model you should follow several steps:

1. To define the child domain, click "Define child" and create the child domain on the main window. The size of the grid child (Lchild and Mchild) is now visible. This operation can be redone until you are satisfied with the size and the position of the child domain. The child domain can be finely tuned using the imin, imax, jmin and jmax boxes. Be aware that the mask interpolation from the parent grid to the child grid is not optimal close to corners. Parent/Child boundaries should be placed where the mask is showing a straight coastline. A warning will be given during the interpolation procedure if this is not the case.
2. "Interp child" : It generates the child grid file. Before, you should select if you are using a new topography ("New child topo" button) for the child grid or if you are just interpolating the parent topography on the child grid. In the first case, you should defines what topography



Figure 8: The NestGUI main window

- file will be used (e.g. `~/Roms_tools/Topo/etopo2.nc` or another dataset). You should also define if you want the volume of the child grid to match the volume of the parent close to the parent/child boundaries ("Match volume" button, it should be "on" by default). You should also define the r factor (Beckmann and Haidvogel, 1993) for topography smoothing ("r-factor", 0.25 is safe) and the number of points to connect the child topography to the parent topography ("n-band", it follows the relation $h_{new} = \alpha \cdot h_{child} + (1 - \alpha) \cdot h_{parent}$, where α is going from 0 to 1 in "n-band" points from the parent/child boundaries). You should also select the child minimum depth ("Hmin", it should be lower or equal to the parent minimum depth), the maximum depth at the coast ("Hmax coast"), the number of selective hanning filter passes for the deep regions ("n filter deep") and the number of final hanning filter passes ("n filter final").
3. "Interp forcing": It interpolates the parent surface forcing on the child grid. Select the parent forcing file to be interpolated (e.g. `~/Roms_tools/Run/ROMSFILES/roms_frc.nc`). The child forcing file `roms_frc.nc.1` will be created. The parent surface fluxes are interpolated on the child grid. You can use "Interp bulk" if you are using a bulk formula. In this case, the parent bulk file (e.g. `~/Roms_tools/Run/ROMSFILES/roms_blk.nc`) will be interpolated on the child grid.
 4. "Interp initial": It interpolates parent initial conditions on the child grid. Select the parent initial file (e.g. `~/Roms_tools/Run/ROMSFILES/roms_ini.nc`). The child initial file (e.g. `~/Roms_tools/Run/ROMSFILES/roms_ini.nc.1`) will be created. If the topographies are different between the parent and the child grids, the child initial conditions are vertically re-interpolated. In this case you should check if the options "vertical corrections" and "extrapolations" are selected. "Interp biology" can be used to interpolate parent biological variables for biogeochemical experiments. "Interp restart" generates a child restart file from a parent restart file (e.g. `~/Roms_tools/Run/ROMSFILES/roms_rst.nc`). This can be done to "hot start" a child model after the spin-up of the parent model.

5. You can click on "Create roms.in.*" to generate a child input file (roms.in.1) from the parent input file and click on "Create AGRIF_FixedGrids.in" to generate a AGRIF_FixedGrids.in file (the file which defines the child grid position in the parent grid).

"river" can be used to locate the river on the coast. "Interp clim" can be useful to generate boundary conditions to test the child model alone.

6.3 Compiling and running the model

The ROMS nesting procedure needs a Fortran 95 compiler. For Linux PCs, the Intel Fortran Compiler (ifort) is available at <http://www.intel.com/software/products/compilers/flin/noncom.htm>. To be able to compile ROMS with ifort, you should change the corresponding comments in jobcomp. Define AGRIF in ~/Roms_tools/Run/cppdefs.h. Other cpp keys are related to AGRIF:

- AGRIF_OBC_EAST : Open eastern boundary for the child grids.
- AGRIF_OBC_WEST : Open western boundary for the child grids.
- AGRIF_OBC_SOUTH : Open southern boundary for the child grids.
- AGRIF_OBC_NORTH : Open northern boundary for the child grids.
- AGRIF_STORE_BAROT_CHILD : Store ubar and vbar during the parent step for the child boundary conditions.
- AGRIF_FLUX_BC : Apply parent/child barotropic boundary conditions has fluxes.
- AGRIF_POLY_DUAVG : Apply a third order polynomial temporal interpolation for DU_avg1 and DU_avg2.
- AGRIF_LOCAL_VOLCONS : Enforce parent-child mass conservation.
- AGRIF_OBC_M2FLATHER : Activate Flather open boundary conditions for ubar and vbar for the child model .
- AGRIF_OBC_M2ORLANSKI : Activate 2D radiation open boundary conditions for ubar and vbar for the child model.
- AGRIF_OBC_M2SPECIFIED : Activate specified open boundary conditions for ubar and vbar for the child model.
- AGRIF_OBC_M2CHARACT : Activate open boundary conditions based on characteristic methods for ubar and vbar for the child model.
- AGRIF_OBC_M3ORLANSKI : Activate 2D radiation open boundary conditions for u and v for the child model.
- AGRIF_OBC_M3SPECIFIED : Activate specified open boundary conditions for u and v for the child model.
- AGRIF_OBC_M3CHARACT : Activate open boundary conditions based on characteristic methods for u and v for the child model.
- AGRIF_OBC_TORLANSKI : Activate 2D radiation open boundary conditions for tracers for the child model .
- AGRIF_OBC_TUPWIND : Activate upwind open boundary conditions for tracers for the child model.
- AGRIF_OBC_TSPECIFIED : Activate specified open boundary conditions for tracers for the child model.

The default definitions should be sufficient for most of the applications.

It is possible to edit the file `AGRIF_FixedGrids.in`. This file contains the child grid positions (i.e. `imin,imax,jmin,jmax`) and coefficients of refinement. A first line gives the number of children grids per parent (if `AGRIF_STORE_BAROT_CHILD` is defined, only one child grid can be defined per parent grid). A second line gives the relative position of each grid and the coefficient of refinement for each dimension. Edit the input files `roms.in.1`, `roms.in.2`, etc... to define correctly the file names and the time steps. To run the model, simply type at the prompt: `roms roms.in`.

To visualize the ROMS model outputs for different grid levels, change the value in the "child models" box in `roms_gui`.

7 Biology

ROMSTOOLS can help for the design of ROMS biogeochemical experiments. For the initial conditions and lateral boundary conditions, WOA provides a seasonal climatology for nitrate concentration and WOA or SeaWifs can be used to obtain a seasonal climatology of surface chlorophyll concentration. Phytoplankton is estimated by a constant chlorophyll/phytoplankton ratio derived from previous simulations. Zooplankton is estimated in a similar way. The part which should be edited by the user in `romstools_param.m` is:

```
%%%%%%%%%%
%
% Open boundaries and initial conditions parameters
% used by make_clim.m, make_biol.m, make_bry.m
%%%%%%%%%%
%
% World Ocean Atlas directory (WOA2001 or WOA2005)
%
woa_dir=[ROMSTOOLS_dir,'WOA2005/'];
%
% Surface chlorophyll seasonal climatology (WOA2001 or SeaWifs)
%
chla_dir=[ROMSTOOLS_dir,'SeaWifs/'];
%
```

Variables description :

- `woa_dir=[ROMSTOOLS_dir,'WOA2005/']` : Directory where the World Ocean Atlas 2005 climatology (Conkright et al., 2002) is located. The World Ocean Atlas 2001 climatology can also be used.
- `chla_dir=[ROMSTOOLS_dir,'SeaWifs/']` : Directory of the surface chlorophyll seasonal climatology.

Run `make_biol` in the Matlab session :

```
>>
>> make_biol
```

You should obtain :

Add_no3: creating variables and attributes for the OA file
Add_no3: creating variables and attributes for the Climatology file

Ext tracers: Roa = 0 km - default value = NaN
Ext tracers: horizontal interpolation of the annual data

Ext tracers: horizontal interpolation of the seasonal data

time index: 1 of total: 4

time index: 2 of total: 4

time index: 3 of total: 4

time index: 4 of total: 4

Vertical interpolations

NO3...

Time index: 1 of total: 4

Time index: 2 of total: 4

Time index: 3 of total: 4

Time index: 4 of total: 4

CHla...

Add_chla: creating variable and attribute

...

Make a few plots...

The cpp keys related to biology:

- BIO_NChlPZD : Select a 5 components (Nitrate, Chlorophyll, Phytoplankton, Zooplankton, Detritus) biogeochemical model.
- BIO_N2ChlPZD2 : Select a 7 components (Nitrate, Ammonium, Chlorophyll, Phytoplankton, Zooplankton, Small Detritus, Large Detritus) biogeochemical model.
- BIO_N2P2Z2D2 : Select a 8 components (Nitrate, Ammonium, Small Phytoplankton, Large Phytoplankton, Small Zooplankton, Large Zooplankton, Small Detritus, Large Detritus) biogeochemical model.
- DIAGNOSTICS_BIO : Define if writing out fluxes between the biological components.

8 Operational coastal modeling system

An operating coastal modeling system can be designed following the assumption that large scale offshore dynamics are slow in comparison to the coastal system. The lateral boundary conditions are interpolated from the last available ECCO model outputs and are kept constant during the ROMS simulation. ECCO model outputs are delayed by about two to four weeks, but we suppose that they are still relevant for the present large scale oceanic structure. The Global Forecast System (GFS) is used for the surface forcing. A first day of simulation is run in hindcast mode. This will provide the initial conditions for the next simulated day. Using GFS as surface forcing and ECCO for the lateral boundary conditions, a forecast of 7 days is conducted. A UNIX C-Shell script (/Roms_tools/Run/run_roms_forecast.csh) manages data downloading, the hindcast and forecast simulations and data storage. The script run_roms_forecast.csh starts Matlab in batch mode to download with OPENDAP the lateral boundary conditions from ECCO and the surface forcing from GFS. It interpolates the data on ROMS grid and launches the hindcast and the forecast runs.

The script run_roms_forecast.csh should be edited to change the directory pathways (HOME, RUNDIR, PATH, LD_LIBRARY_PATH, MATLAB,...).

The ROMS input files ~/Roms_tools/Run/roms_hindcast.in and ~/Roms_tools/Run/roms_forecast.in should also be edited to change the length of the time step and the number of time steps. The ROMS input file roms_hindcast.in should be defined such as the hindcast run duration is 1 day and a restart file is generated at the end of the hindcast run.

The script run_roms_forecast.csh can be relaunched everyday in batch mode using crontab.

References

- Beckmann, A., Haidvogel, D.B., 1993. Numerical simulation of flow around a tall isolated seamount. Part I: Problem formulation and model accuracy. *Journal of Physical Oceanography* 23, 1736-1753.
- Blanke, B., Roy, C., Penven, P., Speich, S., McWilliams, J.C., Nelson, G., 2002. Linking wind and upwelling interannual variability in a regional model of the southern Benguela, *Geophysical Research Letters* 29, 2188-2191.
- Blayo, E., Debreu, L., 1999. Adaptive mesh refinement for finite-difference ocean models: First experiments. *Journal of Physical Oceanography* 29, 1239-1250.
- Carton, J.A., Giese, B.S., Grodsky, S.A., 2005. Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis. *Journal of Geophysical Research* 110, C09006, doi:10.1029/2004JC002817.
- Casey, K.S., Cornillon, P., 1999. A comparison of satellite and in situ based sea surface temperature climatologies. *Journal of Climate* 12, 1848-1863.
- Conkright, M.E., R.A. Locarnini, H.E. Garcia, T.D. O'Brien, T.P. Boyer, C. Stephens, J.I. Antonov, 2002. World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures, CD-ROM Documentation. National Oceanographic Data Center, Silver Spring, MD, 17 pp.
- Da Silva, A.M., Young, C.C., Levitus, S. 1994. Atlas of surface marine data 1994, Vol. 1, algorithms and procedures, NOAA Atlas NESDIS 6, U. S. Department of Commerce, NOAA, NESDIS, USA, 74 pp.
- Debreu, L., 2000. Raffinement adaptatif de maillage et méthodes de zoom - application aux modèles d'océan, 2000, Ph.D. thesis, Université Joseph Fourier, Grenoble.
- Debreu, L., Blayo, E., 2003. AGRIF: Adaptive Grid Refinement In Fortran. *submitted to ACM Transactions on Mathematical Software - TOMS*.
- Debreu, L., Vouland, C., 2003. AGRIF: Adaptive Grid Refinement In Fortran. [Available online <http://www-lmc.imag.fr/IDOPT/AGRIF/index.html>].
- Di Lorenzo, E., Miller, A.J., Neilson, D.J., Cornuelle, B.D., Moisan, J.R., 2003. Modeling observed California Current mesoscale eddies and the ecosystem response. *International Journal of Remote Sensing*, in press.
- Egbert, G., Erofeeva, S., 2002. Efficient inverse modeling of barotropic ocean tides, *Journal of Atmospheric and Oceanic Technology* 19, 183-204.
- Flather, R.A., 1976. A tidal model of the northwest European continental shelf. *Mémoires de la Société Royale des Sciences de Liège*, 10, 141-164.
- Haidvogel, D.B., Arango, H.G., Hedstrom, K., Beckmann, A., Malanotte-Rizzoli, P., Shchepetkin, A.F., 2000. Model Evaluation Experiments in the North Atlantic Basin: Simulations in Nonlinear Terrain-Following Coordinates. *Dynamics of Atmospheres and Oceans* 32, 239-281.
- Haney, R.L., 1991. On the pressure force over steep topography in sigma coordinate ocean models. *Journal of Physical Oceanography* 21, 610-619.
- Jackett, D.R., McDougall, T.J., 1995. Minimal Adjustment of Hydrostatic Profiles to Achieve Static Stability. *Journal of Atmospheric and Oceanic Technology* 12, 381-389.
- Large, W.G., McWilliams, J.C., Doney, S.C., 1994. Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization. *Reviews in Geophysics* 32, 363-403.

- MacCready, P. M., R. D. Hetland, W. R. Geyer, Long-Term Isohaline Salt Balance in an Estuary. *Continental Shelf Research*, 22, 1591-1601.
- Marchesiello, P., McWilliams, J.C., Shchepetkin, A., 2001. Open boundary condition for long-term integration of regional oceanic models. *Ocean Modelling* 3, 1-21.
- Marchesiello, P., McWilliams, J.C., Shchepetkin, A., 2003. Equilibrium structure and dynamics of the California Current System. *Journal of Physical Oceanography* 33, 753-783.
- Penven, P., Roy C., Lutjeharms, J.R.E., Colin de verdière, A., Johnson, A., Shillington, F., Fréon, P., Brundrit, G., 2001. A regional hydrodynamic model of the Southern Benguela. *South African Journal of Science* 97, 472-476.
- Penven, P., Debreu, L., Marchesiello, P., McWilliams, J.C., 2006. Application of the ROMS embedding procedure for the Central California Upwelling System. *Ocean Modelling* 12, 157-187.
- Penven, P., Marchesiello, P., Debreu, L., Lefèvre, J., 2007. Software tools for pre- and post-processing of oceanic regional simulations. *Environmental Modelling and Software*, in press.
- Reynolds, R.W., Smith, T.M., 1994. Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate*. 7, 929-948.
- Shchepetkin, A.F., McWilliams, J.C., 1998. Quasi-monotone advection schemes based on explicit locally adaptive dissipation. *Monthly Weather Review* 126, 1541-1580.
- Shchepetkin, A.F., McWilliams, J.C., 2003. A method for computing horizontal pressure-gradient force in an ocean model with a non-aligned vertical coordinate. *Journal of Geophysical Research* 108.
- Shchepetkin, A.F., McWilliams, J.C., 2005. Regional Ocean Model System: a split-explicit ocean model with a free-surface and topography-following vertical coordinate. *Ocean Modelling* 9, 347-404.
- Smith, W.H.F., Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings. *Science* 277, 1957-1962.
- Stammer, D., Davis, R., Fu, L.L., Fukumori, I., Giering, R., Lee, T., Marotzke, J., Marshall, J., Menemenlis, D., Niiler, P., Wunsch, C., Zlotnicki, V., 1999. The consortium for estimating the circulation and climate of the ocean (ECCO) - Science goals and task plan - Report N°1. Technical report, Jet Propulsion Laboratory - Massachusetts Institute of Technology - Scripps Institution of Oceanography.