1D ROMS model documentation
DRAFT

Part I

Model formulation

This 1D numerical model is derived from the UCLA ROMS 3D ocean model. It keeps the array structure and the vertical position of the variables. The mixing closure sub-model, the treatment of vertical advection and diffusion are compatible with the UCLA ROMS 3D model.

1 Equations of motion

The primitive hydrostatic equations of an ocean with no horizontal variations on a Cartesian frame resumes to:

$$\frac{\partial u}{\partial t} = fv + \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right) \tag{1}$$

$$\frac{\partial v}{\partial t} = -fu + \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right) \tag{2}$$

$$\frac{\partial P}{\partial z} = -\rho g \tag{3}$$

$$\frac{\partial T}{\partial t} = w^* \frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z} - \gamma\right) + \frac{T_{ref} - T}{\tau} \tag{4}$$

$$\frac{\partial S}{\partial t} = w^* \frac{\partial S}{\partial z} + \frac{\partial}{\partial z}\left(K_S \frac{\partial S}{\partial z} - \gamma\right) + \frac{S_{ref} - S}{\tau} \tag{5}$$

$$w = 0 \tag{6}$$

$$\rho = F(T, S, P) \tag{7}$$

With the vertical boundary conditions prescribed as follows:

$$\text{at the top: } z = 0 \quad K_M \frac{\partial u}{\partial z} = \tau^x_{surf} \tag{8}$$

$$K_M \frac{\partial v}{\partial z} = \tau^y_{surf} \tag{9}$$

$$K_T \frac{\partial T}{\partial z} = \frac{Q_T}{\rho_0 C_p} \tag{10}$$

$$K_S \frac{\partial S}{\partial z} = \frac{(E-P)S}{\rho_0} \tag{11}$$

at the bottom: $z = -h$

$$K_M \frac{\partial u}{\partial z} = \tau^x_{bot} \tag{12}$$

$$K_M \frac{\partial v}{\partial z} = \tau^y_{bot} \tag{13}$$

$$K_T \frac{\partial T}{\partial z} = 0 \tag{14}$$

$$K_S \frac{\partial S}{\partial z} = 0 \tag{15}$$

$$\tag{16}$$

Where,

- t is the time variable
- z is the vertical coordinate in the Cartesian frame, increasing towards the top.
- u, v, w are components of the velocity vectors in the Cartesian frame
- f is the Coriolis parameter
- T is the potential temperature of the Ocean
- S is the salinity of the Ocean
- T_{ref} is the potential temperature data towards which the temperature is relaxed
- S is the salinity of the Ocean
- S_{ref} is the salinity data towards which the salinity is relaxed
- τ is the nudging relaxation time towards data
- P is the total pressure
- F is an equation of state of sea water
- ρ is the in-situ density perturbation
- ρ_0 is the mean density
- g is the acceleration of gravity
- K_M, K_T, K_S are the vertical turbulent mixing coefficients, defined by the KPP vertical turbulent closure scheme
- γ is a nonlocal transport term in addition to the down-gradient component

- τ^x_{surf}, τ^y_{surf} are the surface wind stress components
- Q_T is the surface heat flux
- $E - P$ is the evaporation minus the precipitation
- τ^x_{bot}, τ^y_{bot} are the bottom stress components, they are set to 0
- h is the depth of the water column
- w^* is an artificial vertical velocity introduced to take the effects of an upwelling into account

Equations (1) and (2) express the momentum balance in the x and y directions. Under the hydrostatic approximation, the momentum balance (equation 3)in the vertical direction limits itself to a balance between the pressure gradient and the buoyancy forces. Equations (4) and (5) express the time evolution of Temperature and Salinity. Equation (6) expresses the continuity equation for an incompressible fluid, that implies in a 1D model the vertical velocities to be null. Equation (7) gives the equation of state.

2 The stretched vertical coordinate system

(setup_grid.F)

The equations of motion are discretized following a non-linear vertical coordinate, in order to increase the resolution near the surface boundary layer. The grid is staggered, with the 'w' points positioned between the 'ρ' points.

$$z_\rho(i) = -\frac{h \sinh\left(\theta_s \frac{N-i+0.5}{N}\right)}{\sinh(\theta_s)}; \quad i = \{1, 2, \dots, N\} \tag{17}$$

$$z_w(i) = -\frac{h \sinh\left(\theta_s \frac{N-i}{N}\right)}{\sinh(\theta_s)}; \quad i = \{0, 1, \dots, N\} \tag{18}$$

$$H_z(i) = N\left(z_w(i) - z_w(i-1)\right); \quad i = \{1, 2, \dots, N\} \tag{19}$$

3 Forcing

(set_forces.F)

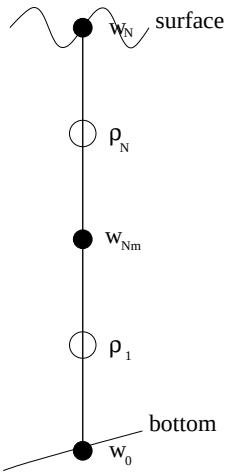

Figure 1: Position of variables on the staggered grid.

The model has been setup to run on a yearly cycle using monthly forcing data. These data are stored in an ASCII file 'forces.data':

SUSTR "surface u-momentum stress" "Newton meter-2"
0.0109 0.0148 0.0236 0.0248 0.0265 0.0242
0.0207 0.0204 0.0185 0.015 0.0125 0.0082

SVSTR "surface v-momentum stress" "Newton meter-2"
...

The temporal mean of the heat and salinity fluxes are removed in order to obtain a yearly cyclic solution. A temporal linear interpolation is achieved to get the forcing at each model time step. A diurnal cycle is added to the solar short-wave radiation flux as a function of the latitude.

4 Upwelling

(step3dS.F)

An arbitrary vertical velocity w^* can be introduced to account for a possible upwelling that could bring tracers towards the surface (cpp key: UPWELLING). This velocity is function of an upwelling index (UPW [m^3/s/100m of coastline]) which is given by the forcing file. Upwelling

indices can be found at
http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html
The vertical velocity is defined in such a way that it is zero at surface and at bottom and it is maximum at a given depth (z_{wmax} = -100 m, defined in step3dS.F). Three different vertical profiles can be chosen:

- Linear (cpp key: LINEAR_W):

$$w^* = \frac{\text{UPW}}{100.L} \begin{cases} \frac{z}{z_{wmax}} & \text{for } z \geq z_{wmax} \\ \frac{z+h}{z_{wmax+h}} & \text{for } z < z_{wmax} \end{cases} \tag{20}$$

- Sinusoïdal (cpp key: SINUS_W):

$$w^* = \frac{\text{UPW}}{100.L} \begin{cases} \sin\left(\frac{\pi}{2}\frac{z}{z_{wmax}}\right) & \text{for } z \geq z_{wmax} \\ \sin\left(\frac{\pi}{2}\frac{z+h}{z_{wmax+h}}\right) & \text{for } z < z_{wmax} \end{cases} \tag{21}$$

- Parabolic (cpp key: PARAB_W):

$$w^* = \frac{\text{UPW}}{100.L} \begin{cases} \frac{-1}{z_{wmax}^2} z^2 + \frac{2}{z_{wmax}} z & \text{for } z \geq z_{wmax} \\ \frac{-1}{(z_{wmax}+h)^2} z^2 + \frac{2 z_{wmax}}{(z_{wmax}+h)^2} z + 1 - \left(\frac{z_{wmax}}{z_{wmax}+h}\right)^2 & \text{for } z < z_{wmax} \end{cases} \tag{22}$$

Where,

- $z_{wmax} = -100$ m is the vertical position of the maximum in vertical velocities
- L is the cross shore length scale of the problem. Here, $L = 300$ km.

If the upwelling is on, an additional term can be added in the tracer equation to take into account the global horizontal transport induced by the upwelling in the surface layers (cpp key: EXPORT):

$$\begin{aligned} \bar{u}\frac{\partial T}{\partial x} &\sim \frac{U}{L}\left(T_{\text{off-shore}} - T_{\text{coastal}}\right) \\ &\sim \frac{w^*}{z_{wmax}}\left(T_{\text{off-shore}} - T_{\text{coastal}}\right) \end{aligned} \tag{23}$$

In the model, this term takes the form:

$$\begin{cases} \frac{\text{UPW}}{100.L.z_{wmax}}(T_{ref} - T) & \text{for } z \geq z_{wmax} \\ 0 & \text{for } z < z_{wmax} \end{cases} \tag{24}$$

5 Initial conditions

(setup_initial.F)

The initial variables are set analytically. The horizontal velocities are set to zero (fluid at rest). The tracer fields are given by a set of functions to fit a CalCOFI data mean profile:

$$T_0 = 5 + 1.475 \times 10^{-3} z + 5.65 e^{\frac{z}{100}} + 5 e^{\frac{z}{500}} \quad [^{\circ}\mathrm{C}] \tag{25}$$

$$S_0 = 34.28 - 1.75 \times 10^{-4} z + 0.8 e^{\frac{z}{200}} + 0.2 e^{\frac{z}{400}} \quad [\mathrm{PSU}] \tag{26}$$

The initial value for the vertical mixing coefficients is 0.01 for momentum and 0.001 for tracers. The model can is restart from a file if the cpp key RESTART_OUT is defined.

6 Nudging

If the cpp key NUDGE is defined, temperature and salinity (and for the biology, the nitrates) are relaxed towards their initial values with a relaxation time:

$$\tau = 2 + 23 e^{\frac{z}{100}} \quad [\mathrm{year}^{-1}] \tag{27}$$

It is set such that it climbs to about 5 years below 200 m but decreases to a max of 25 years at the surface.

7 Equation of state

(rho_eos.F)

The density, needed for the turbulent mixing closure scheme, is computed using the equation of state for sea water proposed by Jackett and McDougall (1995). The compression terms are neglected.

$$\begin{aligned} \rho \;=\; & 999.842594 + 6.793952 \times 10^{-2} T - 9.095290 \times 10^{-3} T^2 + 1.001685 \times 10^{-4} T^3 \\ & - 1.120083 \times 10^{-6} T^4 + 6.536332 \times 10^{-9} T^5 \\ & + S \left(\begin{array}{l} 0.824493 - 4.08990 \times 10^{-3} T + 7.64380 \times 10^{-5} T^2 \\ - 8.24670 \times 10^{-7} T^3 + 5.38750 \times 10^{-9} T^4 \end{array} \right) \\ & + \sqrt{S} \left(\begin{array}{l} - 5.72466 \times 10^{-3} + 1.02270 \times 10^{-4} T \\ - 1.65460 \times 10^{-6} T^2 + 4.8314 \times 10^{-4} S \end{array} \right) \quad [\mathrm{kg.m}^{-3}] \end{aligned} \tag{28}$$

8 Mixing closure sub-model

The parameterization of the vertical mixing processes in ROMS is done via a non-local, K-profile planetary (KPP) boundary layer scheme [Large et al.,1994]. Two distinct parameterizations are conducted: one for the ocean interior and one for the oceanic surface boundary layer. The boundary layer depth (h) depends on the surface forcing, the buoyancy and the velocity profile. It is determined by equating a bulk Richardson number relative to the surface to a critical value. Below the boundary layer, the vertical mixing is regarded as the superposition of 3 processes: vertical shear, internal wave breaking, and double diffusion. In the surface layer, the diffusivity is formulated to agree with similarity theory of turbulence. At the base of the surface layer, both diffusivity and its gradient have to match the interior values. A non local convective transport is added to the local down-gradient component. The KPP model has been shown to simulate accurately processes such as convective boundary layer deepening, diurnal cycling, and storm forcing.

8.1 Interior mixing

(lmd_vmix.F)

Richardson number:

$$R_i = \frac{\frac{-g\frac{\partial \rho}{\partial z}}{\rho_0}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \tag{29}$$

$$\begin{aligned} K_M \quad = \quad & \underbrace{10^{-4}}_{\text{wave breaking}} \\ & \underbrace{+ 5.10^{-3} \left(1 - \left(\underbrace{\frac{Ri}{0.7}}_{0 \leq \ldots \leq 1} \right)^2 \right)^3}_{\text{shear instability mixing}} \\ & + \quad \underbrace{0.1}_{\text{static instability (if } \frac{\partial \rho}{\partial z} < 0)} \end{aligned} \tag{30}$$

$$K_T \quad = \quad \underbrace{10^{-3}}_{\text{wave breaking}}$$

$$
\begin{aligned}
&+ \underbrace{5.10^{-3} \left(1 - \left(\underbrace{\frac{Ri}{0.7}}_{0 \leq \ldots \leq 1} \right)^2 \right)^3}_{\text{shear instability mixing}} \\
&+ \underbrace{0.1}_{\text{static instability (if } \frac{\partial \rho}{\partial z} < 0)} \\
&+ \underbrace{K_T^{dd}}_{\text{double diffusion}}
\end{aligned}
\tag{31}
$$

8.2 Double diffusion

double-diffusion density ration R_ρ:

$$
R_\rho = \frac{\alpha \frac{\partial T}{\partial z}}{\beta \frac{\partial S}{\partial z}} \tag{32}
$$

Where α and β are the thermodynamic expansion coefficients for temperature and salinity.

- Salt fingering case: warm salty water over cold fresh water ($R_\rho > 1$ and $\beta \frac{\partial S}{\partial z} > 0$):

$$
K_T^{dd} = 7.10^{-4} \left(1 - \left(\frac{min(R_\rho, 1.9) - 1}{0.9} \right)^2 \right)^3 \tag{33}
$$

$$
K_S^{dd} = 10^{-3} \left(1 - \left(\frac{min(R_\rho, 1.9) - 1}{0.9} \right)^2 \right)^3 \tag{34}
$$

- Diffusive convection case: cold fresh water over warm salty water ($0 < R_\rho < 1$ and $\beta \frac{\partial S}{\partial z} < 0$):

$$
K_T^{dd} = 1.3635 \times 10^{-6} e^{\left(4.6 e^{\left(-0.54 (R_\rho^{-1} - 1) \right)} \right)} \tag{35}
$$

$$
K_S^{dd} = \begin{cases} 0.15 K_T^{dd} R_\rho & \text{for } R_\rho < 0.5 \\ K_T^{dd} (1.85 R_\rho - 0.85) & \text{otherwise} \end{cases} \tag{36}
$$

8.3 Boundary layer mixing

(lmd_kpp.F, lmd_swfrac.F, lmd_wscale.F)

8.3.1 Thickness of the boundary layer

Compute the depth (h_{bl}) at which the bulk Richardson number reaches its critical value ($Ri_c = 0.3$).

$$Ri_{bulk}(h_{bl}) = \frac{-g(\rho_{surf} - \rho(h_{bl}))h_{bl}}{\rho_0 \left[\left(u_{surf} - u(h_{bl})\right)^2 + \left(v_{surf} - v(h_{bl})\right)^2 + V_t^2(h_{bl}) \right]} = Ri_c = 0.3 \tag{37}$$

Where $\frac{V_t}{h_{bl}}$ is the turbulent velocity shear:

$$V_t^2(h_{bl}) = \frac{C_v \sqrt{-\beta_T}}{Ri_c \kappa^2} \sqrt{c_s \epsilon} h_{bl} N w_s \tag{38}$$

Where,

- $Cv = 1.8$: ratio of the interior Brunt-Väisälä frequency to the Brunt-Väisälä frequency at the entrainment depth
- $\beta_T = -0.2$: ratio of entrainment buoyancy flux to surface buoyancy flux
- $\kappa = 0.4$: von Kármán's constant
- $c_s = 98.96$ constant used in the calculation of the dimensionless flux profiles
- $\epsilon = 0.1$ non-dimensional extent of the surface layer
- N Brunt-Väisälä frequency
- w_s turbulent velocity scale for scalars

In case of stable buoyancy forcing ($B_f > 0$), h_{bl} is taken as the minimum of the h_{bl} computed above, the Monin-Obukov length $L_{mo} = \frac{u^{*3}}{\kappa B_f}$ and the Ekman depth $h_e = \frac{0.7u^*}{f}$, where $u^* = \frac{|\tau_0|}{\rho_0}$ is the friction velocity and $B_f = g(\alpha Q_{total} - \beta(E-P)S - \frac{\alpha I h_{bl}}{\rho C_p})$ is the forcing buoyancy. α is the thermal expansion coefficient and β is the saline contraction coefficient.

8.3.2 Turbulent velocity scales

- for scalars:

$$w_s = \begin{cases} \kappa \sqrt[3]{-28.86u^{*3} + 98.96\kappa\sigma w^{*3}} & \text{for } \sigma < \epsilon \\ \kappa \sqrt[3]{-28.86u^{*3} + 98.96\kappa\epsilon w^{*3}} & \text{for } \sigma \geq \epsilon \end{cases} \tag{39}$$

- for momentum:

$$w_m = \begin{cases} \kappa \sqrt[3]{1.26u^{*3} + 8.38\kappa\sigma w^{*3}} & \text{for } \sigma < \epsilon \\ \kappa \sqrt[3]{1.26u^{*3} + 8.38\kappa\epsilon w^{*3}} & \text{for } \sigma \geq \epsilon \end{cases} \tag{40}$$

8.3.3 Profiles of diffusivities

$$K_x = h_{bl} w_x(\sigma) G(\sigma), \quad \text{where } x = M, T, S \tag{41}$$

Where $G(\sigma)$ is a cubic polynomial, such as

$$G(0) = 0 \qquad \text{K=0 at surface} \tag{42}$$

$$\frac{\partial G(0)}{\partial \sigma} = 1 \qquad \text{linear reduction of flux with distance in the surface layer} \tag{43}$$

$$G(1) = \frac{K(h_{bl})}{h_{bl} w(1)} \qquad \left\{ \begin{array}{l} \text{Match of the boundary layer and interior diffusivities} \\ \text{at the bottom of the boundary layer} \end{array} \right. \tag{44}$$

$$\frac{\partial G(1)}{\partial \sigma} = \frac{\partial}{\partial \sigma}\left(\frac{K(h_{bl})}{h_{bl} w(1)}\right) \qquad \left\{ \begin{array}{l} \text{Match of the boundary layer and interior derivatives of} \\ \text{the diffusivities at the bottom of the boundary layer} \end{array} \right. \tag{45}$$

8.3.4 Nonlocal transport

The nonlocal transport term γ is nonzero only for scalars in unstable forcing conditions:

$$\gamma = 10\kappa \sqrt[3]{c_s \kappa \epsilon} \frac{B_f}{h_{bl} w_s} \tag{46}$$

Part II

How to run an experiment

9 System requirement

The program has been compiled on SGI and Sun workstations. The system-dependent part of the Makefile is Makedefs.

10 Getting the code

A tar file containing the program is available at http://www.atmos.ucla.edu/~penven/roms1d

11 Define the cpp keys

(cppdefs.h) Before compiling, different options can be chosen by defining different cpp preprocessing keys in the file cppdefs.h.

- SALINITY: define if using salinity
- NONLIN_EOS: define if using nonlinear equation of state
- LMD_MIXING: select the Large/McWilliams/Doney interior mixing
- LMD_RIMIX: add diffusivity due to shear instability
- LMD_CONVEC: add convective mixing due to shear instability
- LMD_DDMIX: add double-diffusive mixing
- LMD_KPP: select Large/McWilliams/Doney Oceanic Planetary Boundary Layer scheme
- LMD_NONLOCAL: turn on or off nonlocal transport
- BIOLOGY: turn on or off the biological module
- BIO_OCEAN: set the biological module to oceanic species
- UPWELLING: turn on or off the upwelling
- LINEAR_W: linear profile of vertical velocities

- SINUS_W: sinusoidal profile of vertical velocities
- PARAB_W: parabolic profile of vertical velocities
- EXPORT: parameterization of horizontal transport
- OXYGEN: define if using oxygen
- NCARG: define if using in-line NCAR graphics plotting routines
- NUDGE: nudging of tracers towards the initial values
- RESTART_OUT: define if writing in a restart output file
- RESTART_IN: define if reading initial values in a restart input file
- BIN_OUTPUT: define if writing in a binary output file
- ASCII_OUTPUT: define if writing in an ASCII output file

12 Define the vertical grid and the initial conditions

12.1 Vertical grid

The number of vertical levels (N), the Coriolis parameteris (f) and the latitude (latr) are defined in the file param.h. The water column total depth (hmax) and the grid streching parameter (theta_s) are defined in the file setup_grid.F.

12.2 Initial conditions

If not restarting the simulation from a file, initial analytical values of the variables can be changed in the file setup_initial.F.

12.3 Upwelling

The arbitrary function defining the rate of upwelling can be changed in step3dS.F.

12.4 Running parameters

For the moment, the running parameters are defined in main.F.

- dt: time step in seconds

- ntimes: total number time-steps in current run
- nwrite: number of time-steps between making a plot
- noutput: number of time-steps between writing in output file
- nrestart: number of time-steps between writing in restart file
- twrite: number of days before starting to write and to plot

13 Compile

Choose a Makedefs.* that match your system and copy it to Makedefs type make clobber and make all

- make clobber: remove all the executables, the .o files, the .dat files ...
- make clean: remove all the .o files
- make tools: compile mpc (precompiling processor designed to work between CPP and FORTRAN compiler) and cross_matrix (analyzer of dependencies to build the dependencies "Make.depend")
- make depend: apply cross_matrix
- make roms1d: compile the program
- make all: tools + depend + roms1d

14 Prepare the forcing file

The model has been setup in a way that it reads monthly forcing values. The forcing values are stored in the file forces.data.

SUSTR "surface u-momentum stress" "Newton meter-2"
0.0109 0.0148 0.0236 0.0248 0.0265 0.0242
0.0207 0.0204 0.0185 0.015 0.0125 0.0082

These values correspond to the months:

January	February	March	April	May	June
July	August	September	October	November	December

This setup can be changed in the file set_forces.F.

15 Run

Type "roms1d" alone or "roms1d > roms.out &" to have a record of the model evolution

16 Get the results

- If the cpp key NCARG is defined, the NCAR Graphics routines produce a gmeta file containing an image every nwrite time-step during the simulation. This file can be used for a quick check of the results.

- If the cpp key BIN_OUTPUT is defined, all the velocities, all the tracers and the depth of the surface oceanic boundary layer are stored every noutput time-step in single precision into the binary file "fort.70", using the command: write(70) u,v,t,h_{bl}

- If the cpp key ASCII_OUTPUT is defined, the depth of the vertical levels are stored in the file "z.dat", and every noutput time-step,

  - the time is stored in the file "days.dat"
  - the depth of the oceanic boundary layer is stored in the file "zbl.dat"
  - the horizontal velocities are stored in the files "u.dat" and "v.dat"
  - all the tracers are stored in the files "tXX.dat", where XX is 01 for temperature, 02 for salinity, ...

  The variables stored in the ASCII files can be visualized with MATLAB using the function "tzplot(vname)", where vname is the name of the variable: "u", "v", "t01", "t02"...

- If the cpp key RESTART_OUT is defined, every nrestart time-step, all the velocities and all the tracers are stored in double precision into the binary file "fort.50", using the command: write(50) u,v,t
  The number of restart outputs is stored in the ASCII file "fort.51".

References

[1] Jackett, D. R. and T. J. McDougall, Minimal Adjustment of Hydrostatic Profiles to Achieve Static Stability, *J. Atmos. Oceanic Techn.*, *12*, 381-389, 1995.

[2] Large, W. G., J. C. McWilliams, and S. C. Doney, Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, *32*, 363-403, 1994.