Numerical Modelling

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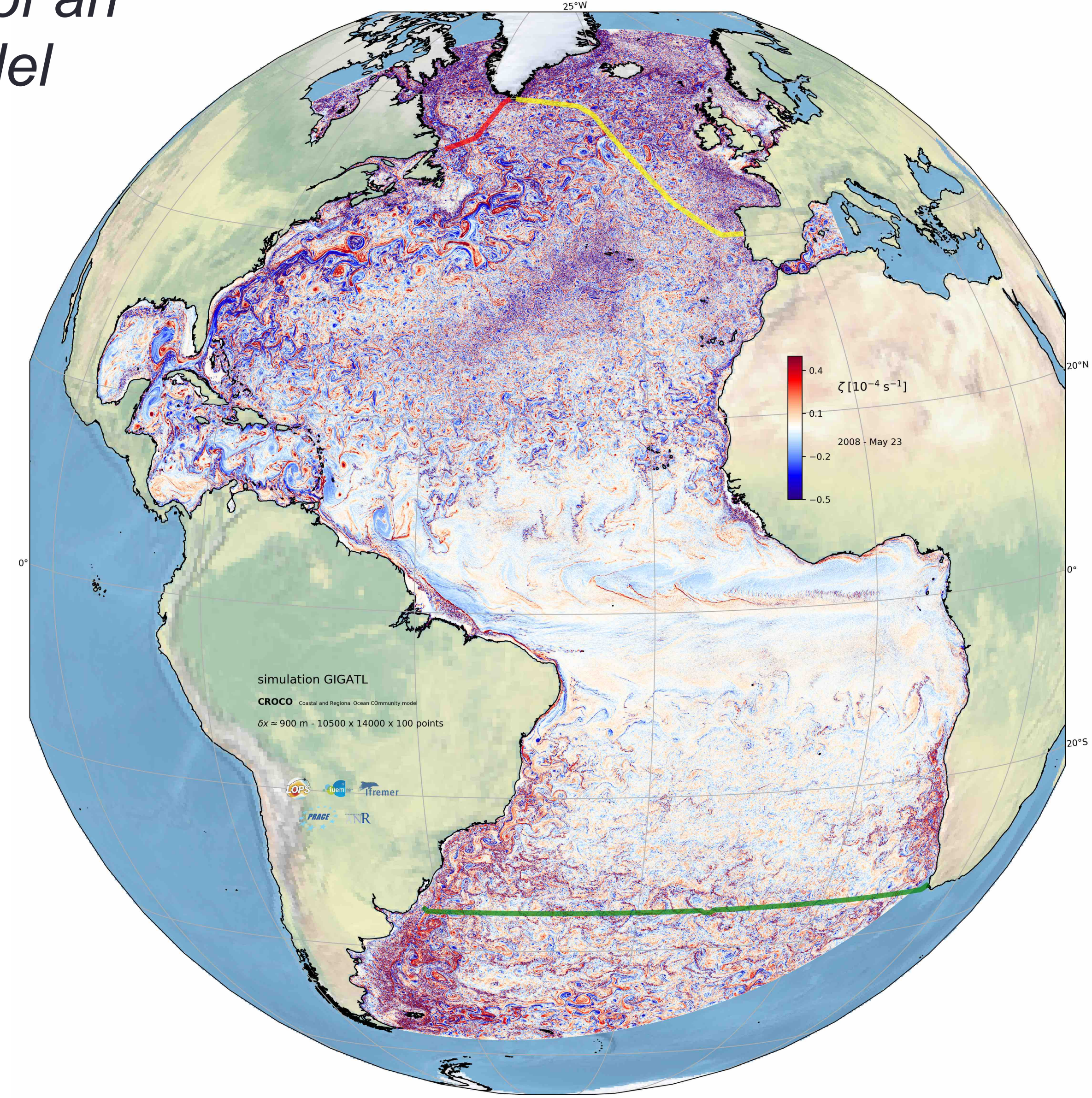
the anatomy of an ocean model



- **Lesson 1 :**
  - Introduction
  - *Activity 1 [run an ocean model]*
- **Lesson 2 :** [B012]
  - Equations of motions
  - Subgrid-scale parameterization
  - *Activity 2 [Dynamics of an ocean gyre]*
- **Lesson 3 :** [D109]
  - Horizontal Discretization
  - Numerical schemes
  - *Activity 3 [Impacts of numerics]*
- **Lesson 4 :** [D109]
  - Vertical coordinates
  - Model parameterizations
  - *Activity 4 [Impact of topography]*
- **Lesson 5 :** [D109]
  - Boundary Forcings
  - Presentation of the model CROCO
  - *Activity 4 [Design a realistic simulation]*
- **Lesson 6 :** [D109]
  - Diagnostics and validation
  - *Activity 5 [Analyze a realistic simulation]*
- **Lesson 7 :** [D109]
  - *Work on your projet*

Presentations and material will be available at :

jgula.fr/ModNum/

Useful references

Extensive courses:

- MIT: https://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-950-atmospheric-and-oceanic-modeling-spring-2004/lecture-notes/
- Princeton: https://stephengriffies.github.io/assets/pdfs/GFM_lectures.pdf

Overview on ocean modelling and current challenges:

- Griffies et al., 2000, Developments in ocean climate modelling, Ocean Modelling.http://jgula.fr/ModNum/Griffiesetal00.pdf
- Griffies, 2006, "Some Ocean Model Fundamentals", In "Ocean Weather Forecasting: An Integrated View of Oceanography", 2006, Springer Netherlands. http://jgula.fr/ModNum/Griffies_Chapter.pdf
- Fox-Kemper et al, 19, “Challenges and Prospects in Ocean Circulation Models" http://jgula.fr/ModNum/FoxKemperetal19.pdf

ROMS/CROCO:

- https://www.myroms.org/wiki/
- Shchepetkin, A., and J. McWilliams, 2005: The Regional Oceanic Modeling System (ROMS): A split-explicit, free-surface, topography-following- coordinate ocean model. Ocean Modell. http://jgula.fr/ModNum/ShchepetkinMcWilliams05.pdf

#1
Which Equations?

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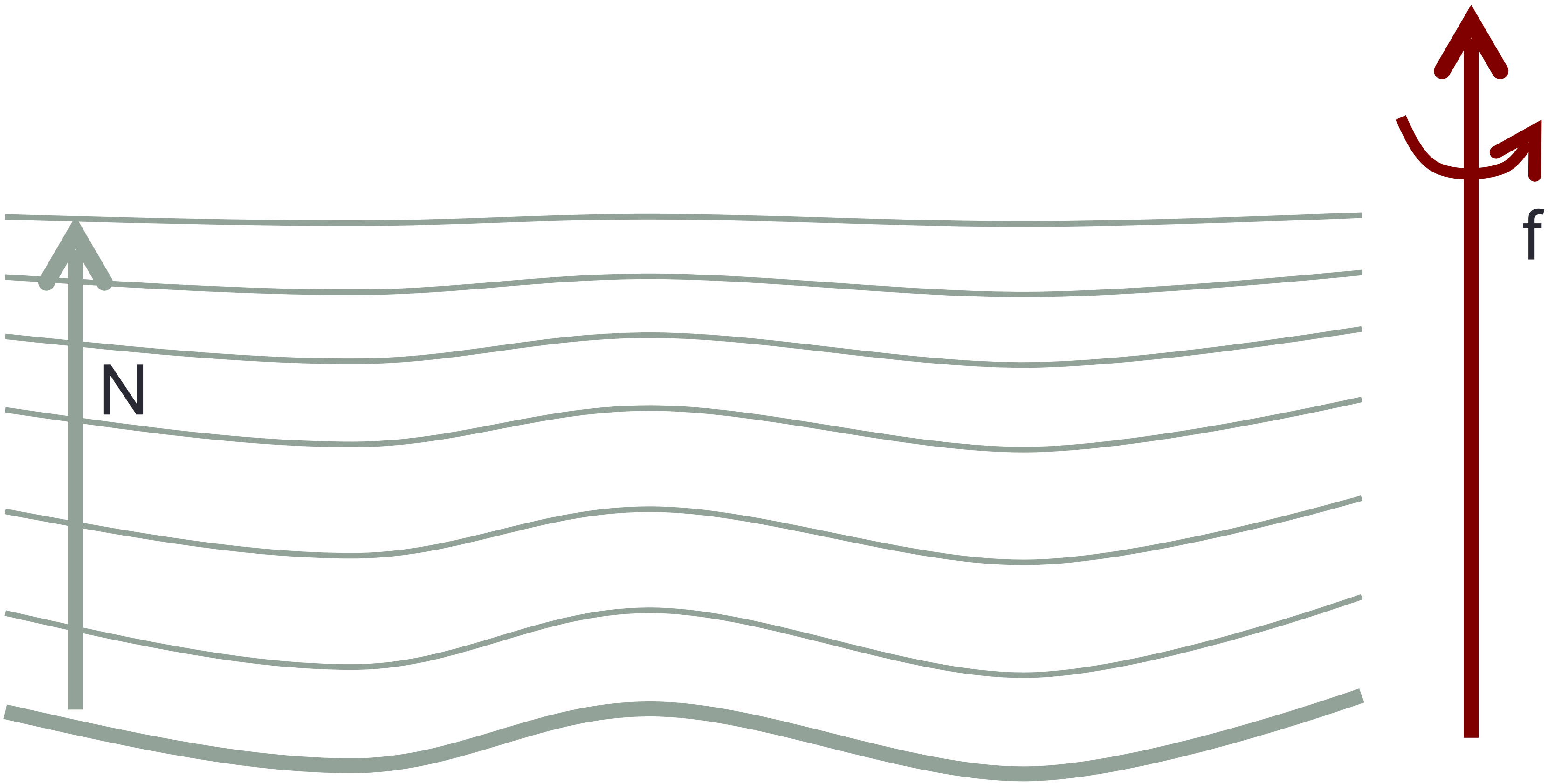
Which Equations?

Ingredients : rotation + stratification



Which Equations?

- Momentum equations (3d) $$\frac{D\vec{u}}{Dt} = \dots$$
- Conservation of mass $$\frac{D\rho}{Dt} = \mathcal{S}_\rho$$
- Conservation of heat $$\frac{DT}{Dt} = \mathcal{S}_T$$
- Conservation of salinity $$\frac{DS}{Dt} = \mathcal{S}_S$$
- Equation of state : $$\rho = \rho(T, S, p)$$

[7 equations for the 7 variables: u,v,w,p,T,S,ρ]

Which Equations?

- Momentum equations (3d) $$\frac{D\vec{u}}{Dt} = \dots$$
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- Equation of state : $$\rho = \rho(T, S, p)$$

[7 equations for the 7 variables: u,v,w,p,T,S,ρ]

Equations for momentum/mass?

- Navier-Stokes Equations (NS)
- Non-hydrostatic Primitive Equations (NH)
- Hydrostatic Primitive Equations (PE)
- Shallow-water (SW)
- Quasi-geostrophic (QG)
- 2D Euler equations
- Etc.

Type of models

Navier Stokes

- DNS = Direct Numerical Simulation
- LES = Large Eddy Simulation

CFD

Process studies

PE

SW

SQG

QG

- PE = Primitive Equations models
- SW = Shallow-Water models
- SQG = Surface Quasi-Geostrophic models
- QG = Quasi-Geostrophic models
- Etc.

Ocean Circulation Models

Idealized models

Equations for momentum/mass?

Navier-Stokes Equations:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \vec{\mathcal{F}}$$

Momentum equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

Mass conservation
(no source/sink)

Equations for momentum/mass?

Navier-Stokes Equations:

$$\boxed{\frac{\partial \vec{u}}{\partial t}} + \boxed{\vec{u} \cdot \vec{\nabla} \vec{u}} + \boxed{2\vec{\Omega} \times \vec{u}} + \boxed{g\vec{k}} = \boxed{-\frac{\vec{\nabla} P}{\rho}} + \boxed{\vec{\mathcal{F}}}$$

Time variation | Advection (inertia) | Rotation | Gravity | Pressure gradient | Forcings + Dissipation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

Mass conservation
(no source/sink)

Equations for momentum/mass?

Navier-Stokes Equations:

Linearized momentum equations

+ continuity equation

+ adiabatic motion :

= Acoustic modes (sound waves)

$$\rho_0 \frac{\partial \vec{u}}{\partial t} = -\vec{\nabla} P$$

$$\frac{\partial P}{\partial t} = -\rho_0 c_s^2 \vec{\nabla} P \cdot \vec{u}$$

$$\partial_{tt} P = c_s^2 \nabla^2 P$$

With $c_s \approx 1500\,\mathrm{m\,s^{-1}}$ in water, a model requires a very small time-step to solve these equations.

Equations for momentum/mass?

Boussinesq Approximation:

Density perturbations small compared to mean background value:

$$\rho = \rho_0 + \rho' \qquad\qquad \rho' << \rho_0$$

Linearize all terms involving a product with density,

except the gravity term which is already linear:

$$\rho\vec{u} \quad \rightarrow \quad \rho_0\vec{u}$$

$$\rho g \quad \rightarrow \quad \rho g$$

Equations for momentum/mass?

Boussinesq Approximation :

[+ incompressibility or adiabatic]

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

$$\Big\downarrow$$

Continuity equation

$$\vec{\nabla} \cdot \vec{u} = 0$$

Equations for momentum/mass?

Non hydrostatic boussinesq (NH):

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\vec{\Omega} \times \vec{u} + \frac{\rho}{\rho_0} g\vec{k} = -\frac{\vec{\nabla} P}{\rho_0} + \frac{\vec{\mathcal{F}}}{\rho_0} + \frac{\vec{\mathcal{D}}}{\rho_0}$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

Easier to solve than Navier-Stokes, but still requires to invert a 3d elliptic equation for P (computationally expansive)

Equations for momentum/mass?

Hydrostatic balance:

The vertical component of the Boussinesq momentum equations is

$$\frac{\partial w}{\partial t} + \vec{u}\cdot\vec{\nabla} w + 2\Omega \cos\phi v + \boxed{\frac{\rho}{\rho_0} g = -\frac{\partial_z P}{\rho_0}} + \frac{\mathcal{F}_w}{\rho_0} + \frac{\mathcal{D}_w}{\rho_0}$$

For long horizontal motions (L >> H) the dominant balance is

H ~3000 m
L ~3000 km

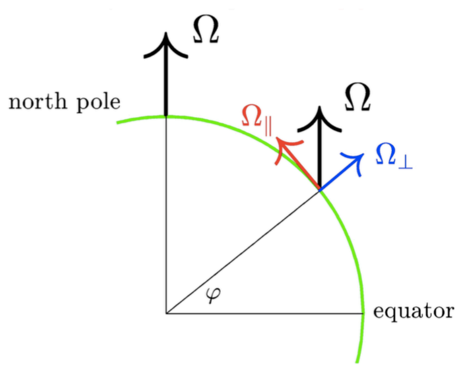
$$\frac{\partial P}{\partial z} = -\rho g$$

Such that pressure is just a vertical integral: $P = \int_z^\eta g\rho dz$

Equations for momentum/mass?

Traditional approximation

= neglect horizontal Coriolis term



$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u} + 2\vec{\Omega}\times\vec{u} + \frac{\rho}{\rho_0} g\vec{k} = -\frac{\vec{\nabla}P}{\rho_0} + \vec{\mathcal{F}} + \vec{\mathcal{D}}$$

$$\Downarrow$$

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u} + f\vec{k}\times\vec{u} + \frac{\rho}{\rho_0} g\vec{k} = -\frac{\vec{\nabla}P}{\rho_0} + \vec{\mathcal{F}} + \vec{\mathcal{D}}$$

Equations for momentum/mass?

Hydrostatic Primitive Equations (PE)

- 2d momentum with Boussinesq approximation:

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla}_H u + w \frac{\partial u}{\partial z} - f v = -\frac{\partial_x P}{\rho_0} + \mathcal{F}_u + \mathcal{D}_u$$
$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla}_H v + w \frac{\partial v}{\partial z} + f u = -\frac{\partial_y P}{\rho_0} + \mathcal{F}_v + \mathcal{D}_v$$

- Hydrostatic: $$\frac{\partial P}{\partial z} = -\rho g$$

- Continuity equation for an incompressible fluid: $\vec{\nabla} \cdot \vec{u} = 0$

Equations for PE Ocean Models

Hydrostatic Primitive Equations (PE)

- 2d momentum with Boussinesq approximation:

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla}_H u + w \frac{\partial u}{\partial z} - f v = -\frac{\partial_x P}{\rho_0} + \mathcal{F}_u + \mathcal{D}_u$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla}_H v + w \frac{\partial v}{\partial z} + f u = -\frac{\partial_y P}{\rho_0} + \mathcal{F}_v + \mathcal{D}_v$$

- Hydrostatic: $$\frac{\partial P}{\partial z} = -\rho g$$
- Continuity equation for an incompressible fluid: $\vec{\nabla} \cdot \vec{u} = 0$
- Conservation of heat and salinity $\frac{DT}{Dt} = \mathcal{S}_T \qquad \frac{DS}{Dt} = \mathcal{S}_S$
- Equation of state : $\rho = \rho(T, S, z)$

Equations for PE Ocean Models

Hydrostatic Primitive Equations (PE)

- 4 prognostics equations for **u, v, T, S**
- 3 diagnostics equations for **w, ρ, P**

Equations for PE Ocean Models

Hydrostatic Primitive Equations (PE)

- 2d momentum with Boussinesq approximation:

?

$$\begin{aligned} \frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla}_H u + w \frac{\partial u}{\partial z} - fv &= -\frac{\partial_x P}{\rho_0} \boxed{+ \mathcal{F}_u + \mathcal{D}_u} \\ \frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla}_H v + w \frac{\partial v}{\partial z} + fu &= -\frac{\partial_y P}{\rho_0} \boxed{+ \mathcal{F}_v + \mathcal{D}_v} \end{aligned}$$

- Hydrostatic: $$\frac{\partial P}{\partial z} = -\rho g$$
- Continuity equation for an incompressible fluid: $$\vec{\nabla} \cdot \vec{u} = 0$$
- Conservation of heat and salinity $$\frac{DT}{Dt} = \boxed{\mathcal{S}_T} \qquad \frac{DS}{Dt} = \boxed{\mathcal{S}_S}$$
- Equation of state : $$\rho = \rho(T, S, z)$$

Equations for PE Ocean Models

Hydrostatic Primitive Equations (PE)

- 4 prognostics equations for **u, v, T, S**
- 3 diagnostics equations for **w, ρ, P**

+ Forcings (wind, heat flux)

+ sub-grid scale parameterizations (bottom drag, mixing, etc.)

#2
Subgrid-scale parameterization

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Incompressible Navier-Stokes Equations:

- Dissipation of energy/momentum in the NS equations:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + f \vec{k} \times \vec{u} + g \vec{k} = -\frac{\vec{\nabla} P}{\rho} + \boxed{\nu \vec{\nabla}^2 \vec{u}}$$

Viscosity

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Ocean Circulation Models

Idealized models

Incompressible Navier-Stokes Equations:

$$\frac{\partial \vec{u}}{\partial t} + \boxed{\vec{u} \cdot \vec{\nabla} \vec{u}} + f\vec{k} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \boxed{\nu \vec{\nabla}^2 \vec{u}}$$

Non-linear terms

Viscosity

- Importance of NL terms and viscosity = Reynolds Number

$$Re = \frac{UL}{\nu}$$

Where *U* is a typical velocity of the flow and *L* is a typical length describing the flow.

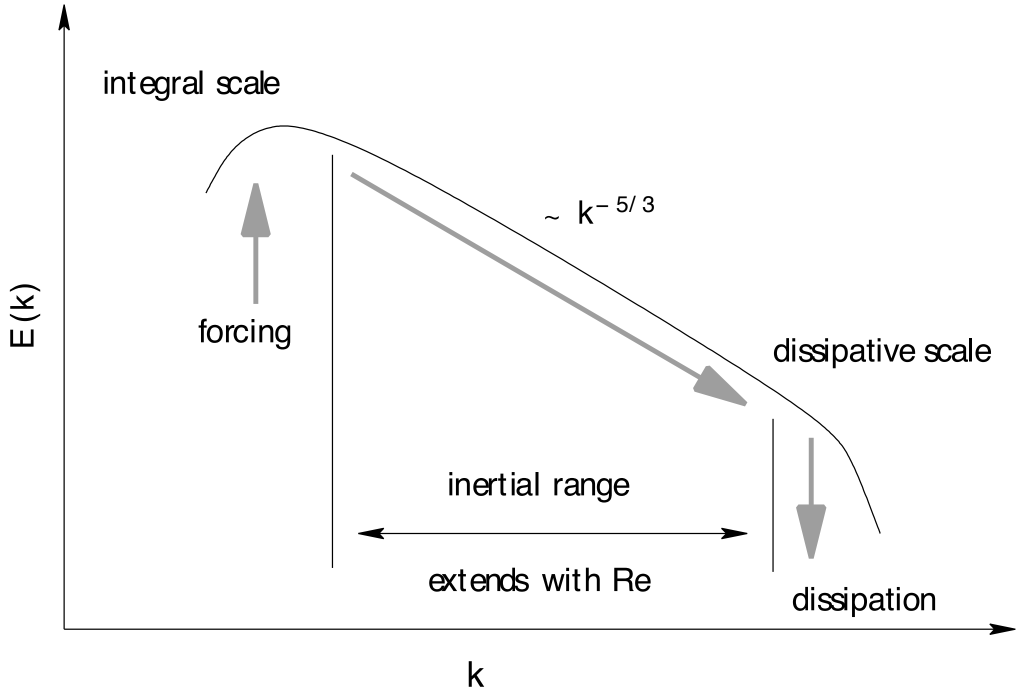
Direct numerical simulation (DNS)

DNS resolves the entire range of turbulent length scales down to the smallest dissipative scales (Kolmogorov scale):

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \approx \left(\frac{\nu^3 L}{U^3}\right)^{1/4} = Re^{-3/4} L$$

where ν is the kinematic viscosity

And ϵ the rate of kinetic energy dissipation



Direct numerical simulation (DNS)

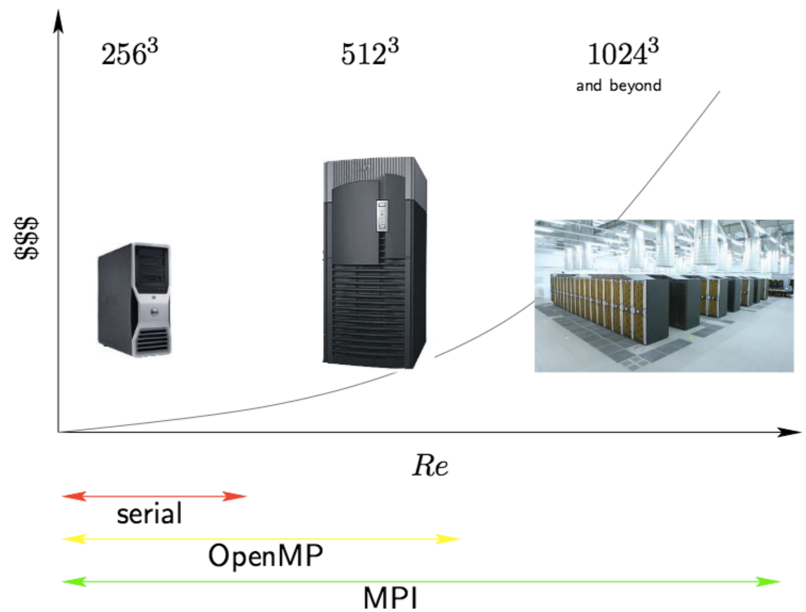
The number of floating-point operations required to complete the simulation is proportional to the number of mesh points:

$$N_x = \frac{L}{\eta} = Re^{3/4}$$

and the number of time steps:

$$\frac{T}{\Delta t} = \frac{TU}{\eta} = \frac{TU}{L} Re^{3/4}$$

It is extremely expensive as the computational cost scales as Re^3



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Ocean Circulation Models

Idealized models

Reynolds averaging

To reduce the computational cost, one need to reduce the range of time- and length-scales that are being solved for.

The idea is based on separation of mean and turbulent component:

$$u = \overline{u} + u'$$

Where

$$\overline{u} = \frac{1}{T}\int_0^T u\; dt \text{ or } \overline{u} = \frac{1}{X}\int_0^X u\; dx$$

With by definition

$$\overline{u'} = 0$$

Reynolds averaging

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u} + f\vec{k}\times\vec{u} + g\vec{k} = -\frac{\vec{\nabla}P}{\rho} + \nu\vec{\nabla}^2\vec{u}$$

- Activity:

Adapt the momentum equation:

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} + f\mathbf{k}\times u_i + \frac{\rho}{\rho_0}g\mathbf{k} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x_j} + \nu\frac{\partial^2 u_i}{\partial x_i \partial x_j}$$

For the mean velocity: $\frac{\partial \overline{u_i}}{\partial t}$ = ?

Reynolds averaging

So we resolve only the equations for the mean variables:

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j \frac{\partial u_i}{\partial x_j}} + f\mathbf{k} \times \overline{u_i} + \frac{\overline{\rho}}{\rho_0} g\mathbf{k} = -\frac{1}{\rho_0}\frac{\partial \overline{P}}{\partial x_j} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} + f\mathbf{k} \times \overline{u_i} + \frac{\overline{\rho}}{\rho_0} g\mathbf{k} = -\frac{1}{\rho_0}\frac{\partial \overline{P}}{\partial x_j} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j} \boxed{- \frac{\partial \overline{u_i' u_j'}}{\partial x_j}}$$

Advection for the averaged flow

Reynolds stress
= effect of subgrid-scale turbulence

Turbulence closure

The Closure Problem :

- The number of unknowns is larger than the number of equations
- When we start deriving equations for unknowns, more variables appear.

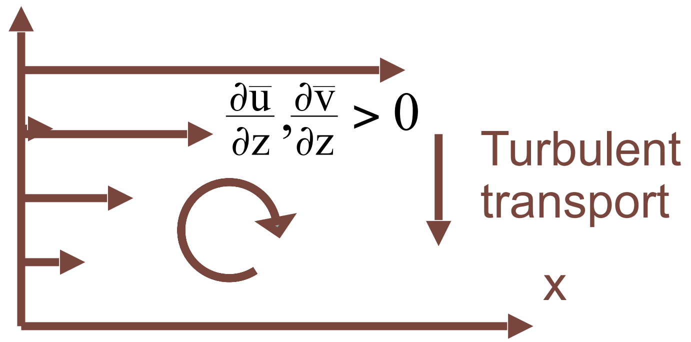
Progn. Eq. for:	Moment	Equation	No. Eqs.	No. Unknowns
$\overline{U_i}$	First	$\frac{\partial \overline{U_i}}{\partial t} = \ldots - \frac{\partial \overline{u'_i u'_j}}{\partial x_j}$	3	6
$\overline{u'_i u'_j}$	First	$\frac{\partial \overline{u'_i u'_j}}{\partial t} = \ldots - \frac{\partial \overline{u'_k u'_i u'_j}}{\partial x_k}$	6	10
$\overline{u'_i u'_j u'_k}$	First	$\frac{\partial \overline{u'_i u'_j u'_k}}{\partial t} = \ldots - \frac{\partial \overline{u'_k u'_i u'_j u'_m}}{\partial x_m}$	10	15

Turbulence closure

- In PE models the equations are closed by parameterizing the Reynolds stresses as:

$$\overline{u'w'} = -K_{Mv}\frac{\partial u}{\partial z}$$

$$\overline{v'w'} = -K_{Mv}\frac{\partial v}{\partial z}$$



Turbulence closure

In ROMS:

$$
\begin{aligned}
\mathcal{F}_u &= \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial u}{\partial z}\right) + \nabla_h(K_{Mh}.\nabla_h u) \\
\mathcal{F}_v &= \frac{\partial}{\partial z}\left(K_{Mv}\frac{\partial v}{\partial z}\right) + \nabla_h(K_{Mh}.\nabla_h v) \\
\mathcal{S}_T &= \frac{\partial}{\partial z}\left(K_{Tv}\frac{\partial T}{\partial z}\right) + \nabla_h(K_{Th}.\nabla_h T) \\
\mathcal{S}_S &= \frac{\partial}{\partial z}\left(K_{Sv}\frac{\partial S}{\partial z}\right) + \nabla_h(K_{Sh}.\nabla_h S)
\end{aligned}
$$

Vertical mixing

Horizontal diffusion

Turbulence closure

Vertical Mixing: K_{Mv}, K_{Tv}, K_{Sv}

- Local Turbulence closure: GLS, k-kl (MY2.5), k-ε, κ-ω, etc. *[e.g. Warner et al, 2005, Ocean Modelling]*
- Non local K-profile parameterization (KPP) *[Large et al, 1994, Rev. of Geophysics]*

Horizontal diffusion: K_{Mh}, K_{Th}, K_{Sh}

- Explicit diffusion
- Implicit (comes from the advective scheme)

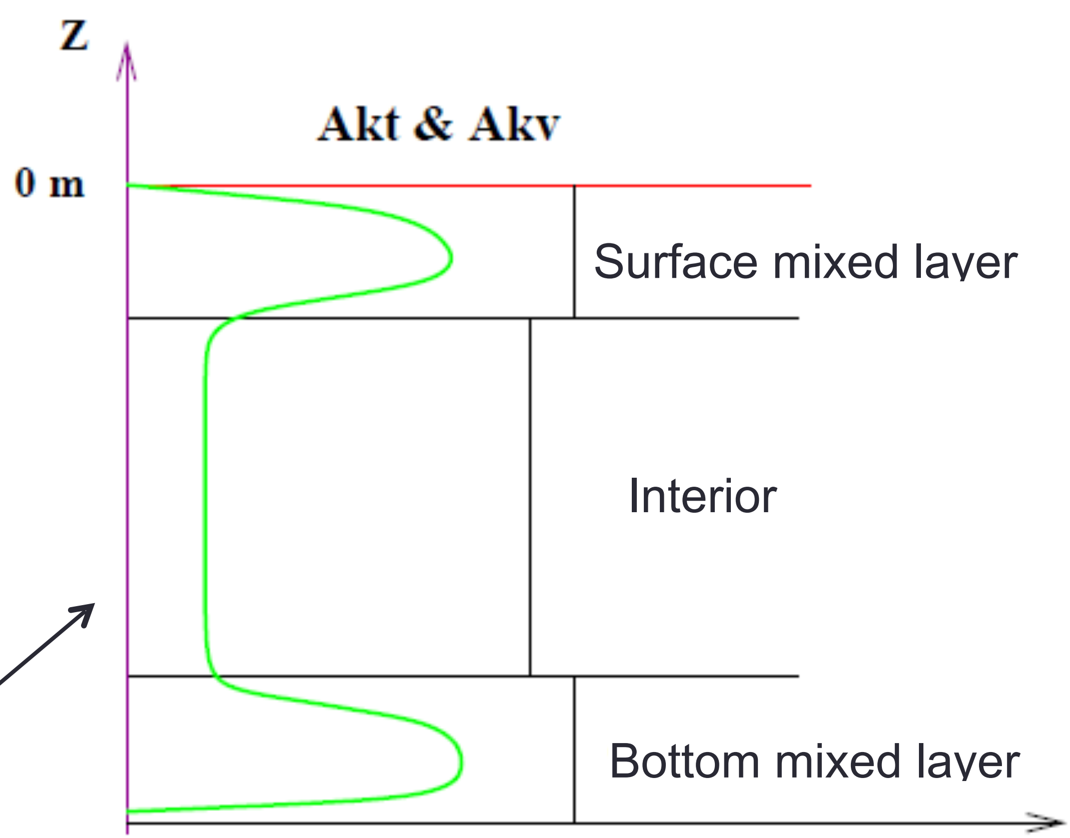
Non local K-profile parameterization

❑ Mixed layer schemes are often based on one-dimensional « column physics »

❑ Boundary layer parameterizations are based either on:

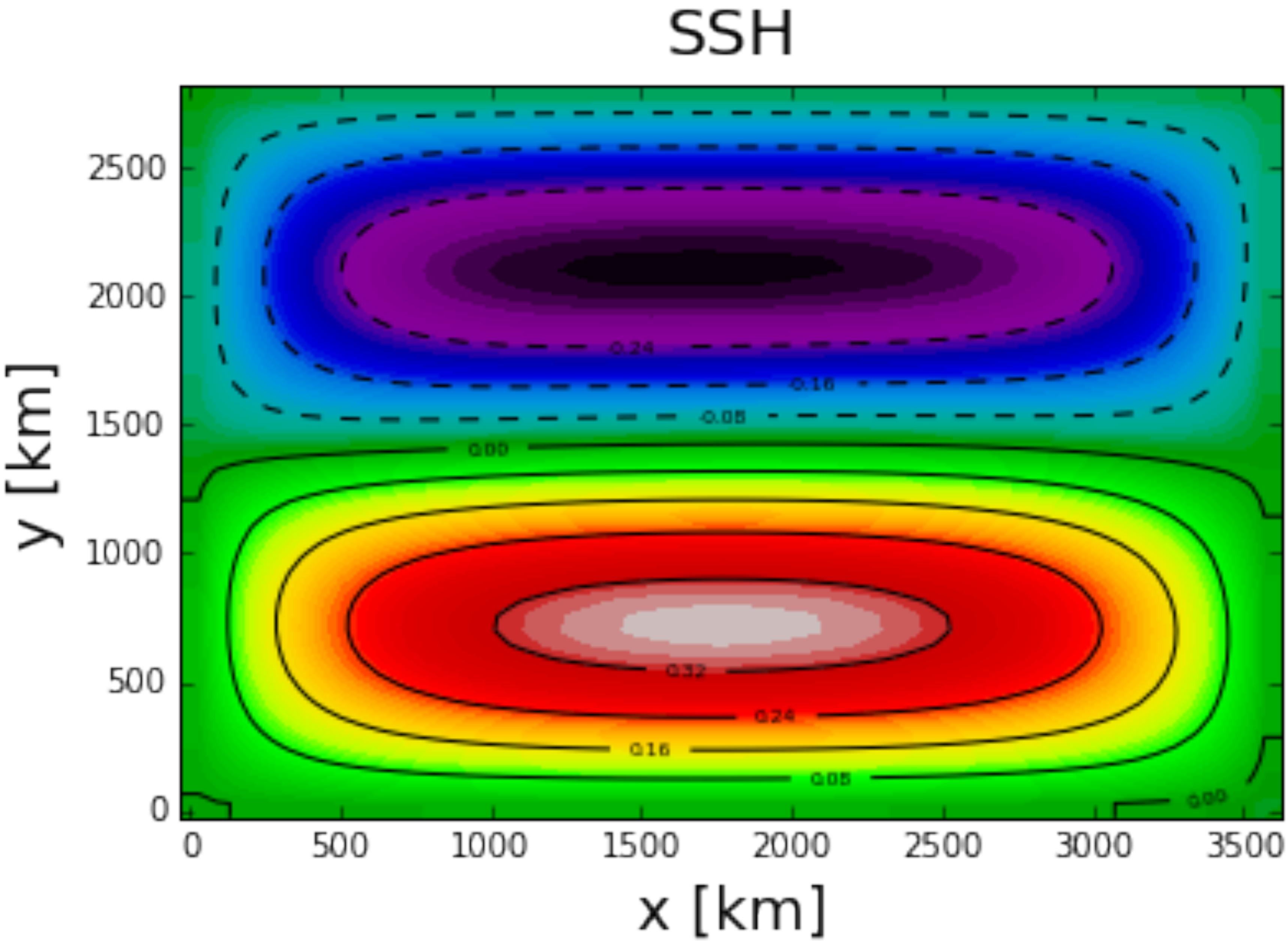
- Turbulent closure (Mellor-Yamada, TKE)
- **K profile (KPP)**

Mixing coefficient profils



Principle scheme of KPP turbulent

Activity 1 – Run an idealized ocean basin



Activity 1 – Run an idealized ocean basin

- **Jobcomp** (compilation)
- **cppdefs.h** (Numerical/physical options)
- **param.h** (gris size/ parallelisation)
- **croco.in** (choice of variables, parameter values, etc.)

1) Preparing and compiling the model

For that use the the jobcomp bash file
./jobcomp

1. Set library path
2. Automatic selection of option accordingly the platform used
3. Use of makefile
   - C-preprocessing step : .F → .f using the CPP keys defintions (in cppdefs.h file, customization of the code)
   - Compilation step : .f → .o (object) using Fortran compiler
   - Linking step : link all the .o file and the librairy (Netcdf, MPI, AGRIF)

     --
   - --> produce the executable roms

1) Preparing and compiling the model

Edit the param.h and cppdefs.h file to set-up the model

param.h defines the size of the arrays in ROMS:

```
...
#elif defined REGIONAL
# if defined BENGUELA
    parameter (LLm0=23, MMm0=31, N=32) <---- Southern Benguela test Model
# else
    parameter (LLm0=??, MMm0=??, N=??)
# endif
...
```

Given by running make_grid

Defined in romstools_param.m

cppdefs.h:

- Basic options
- More advanced options

- Define CPP keys used by the C-preprocessor when compiling the model.
- Reduce the code to its minimal size: fast compilation.
- Avoid FORTRAN logical statements: efficient coding.

1) Preparing and compiling the model

View cppdef.h file

```
!---------------------------------------------------------------
!               BASIC OPTIONS
!---------------------------------------------------------------
*/
/*                      Configuration Name */
# define BENGUELA
/*                      Parallelization */
# undef  OPENMP
# undef  MPI
/*                      Embedding */
# undef AGRIF
/*                      Open Boundary Conditions */
# undef  TIDES
# define OBC_EAST
# undef OBC_WEST
# define OBC_NORTH
# define OBC_SOUTH
*/                       Embedding conditions */
# ifdef AGRIF
#  undef AGRIF_OBC_EAST
#  define AGRIF_OBC_WEST
#  define AGRIF_OBC_NORTH
#  define AGRIF_OBC_SOUTH
# endif
/*                      Applications */
# undef  BIOLOGY
# undef  FLOATS
# undef  STATIONS
# undef  PASSIVE_TRACER
# undef  SEDIMENTS
# undef  BBL
```

```
!---------------------------------------------------------------
!         MORE ADVANCED OPTIONS
!---------------------------------------------------------------
*/
/*                      Model dynamics */
# define SOLVE3D
# define UV_COR
# define UV_ADV
# ifdef TIDES
#  define SSH_TIDES
#  define UV_TIDES
#  define TIDERAMP
# endif
/*                      Grid configuration */
# define CURVGRID
# define SPHERICAL
# define MASKING
/*                          Input/Output & Diagnostics */
# define AVERAGES
# define AVERAGES_K
# define  DIAGNOSTICS_TS
# define  DIAGNOSTICS_UV
/*                          Equation of State  */ ...
/*                          Surface Forcing */ ...
/*                          Lateral Forcing  */ ...
/*                          Input/Output & Diagnostics */ ...
*                           Bottom Forcing  */ ...
/*                          Point Sources - Rivers */ ...
/*                          Lateral Mixing  */ ...
/*                          Vertical Mixing */ ...
/*                          Open Boundary Conditions  */ ...
/*                          Embedding conditions  */ ...
```

2) Running the model

The namelist roms.in

roms.in provides the run time parameters for ROMS:

```
title:
      Southern Benguela
time_stepping: NTIMES   dt[sec]  NDTFAST  NINFO
           480      5400     60      1
S-coord: THETA_S,   THETA_B,    Hc (m)
        6.0d0      0.0d0      10.0d0
grid:  filename
                    ROMS_FILES/roms_grd.nc
forcing: filename
                    ROMS_FILES/roms_frc.nc
bulk_forcing: filename
                    ROMS_FILES/roms_blk.nc
climatology: filename
                    ROMS_FILES/roms_clm.nc
boundary: filename
                    ROMS_FILES/roms_bry.nc
initial: NRREC  filename
        1
                    ROMS_FILES/roms_ini.nc
restart:         NRST, NRPFRST / filename
             480   -1
                    ROMS_FILES/roms_rst.nc
```

Warning ! These should be identical to the ones in romstools_param.m

```
history: LDEFHIS, NWRT, NRPFHIS / filename
         T     480     0
                    ROMS_FILES/roms_his.nc
averages: NTSAVG, NAVG, NRPFAVG / filename
         1      48     0
                    ROMS_FILES/roms_avg.nc

primary_history_fields: zeta UBAR VBAR  U  V   wrtT(1:NT)
                    T    F   F   F  F    10*F
auxiliary_history_fields:   rho Omega  W  Akv  Akt  Aks  HBL  Bostr
                      F   F     F   F    F    F    F    F
primary_averages: zeta UBAR VBAR  U  V   wrtT(1:NT)
               T    T    T    T  T   10*T
auxiliary_averages: rho Omega  W  Akv  Akt  Aks  HBL  Bostr
                F   T     T   F    T    F    T    T
rho0:
     1025.d0
lateral_visc:   VISC2,    VISC4    [m^2/sec for all]
              0.      0.
tracer_diff2: TNU2(1:NT)          [m^2/sec for all]
             10*0.d0
bottom_drag:    RDRG [m/s],  RDRG2,  Zob [m],  Cdb_min, Cdb_max
              0.0d-04     0.d-3     1.d-2     1.d-4     1.d-1
gamma2:
              1.d0
sponge:          X_SPONGE [m],    V_SPONGE [m^2/sec]
               100.e3          800.

nudg_cof:    TauT_in, TauT_out, TauM_in, TauM_out  [days for all]
             1.       360.      10.      360.
```

Activity 1 – Run an idealized ocean basin

- **param.h**

```
     parameter (LLm0=60,   MMm0=50,   N=10)
```

- **cppdefs.h**

```
# define UV_COR
# define UV_VIS2
# define TS_DIF2

# define ANA_GRID
# define ANA_INITIAL
```

- **ana_grid.F**

```
f0=1.E-4
beta=0.
```

- **croco.in**

```
bottom_drag:     RDRG(m/s),      RDRG2, Zob [m],  Cdb_min, Cdb_max
                 3.e-4             0.      0.         0.      0.
gamma2:
                 1.
lin_EOS_cff:  R0 [kg/m3], T0 [Celsius], S0 [PSU], TCOEF [1/Celsius], SCOEF [1/PSU]
              30.          0.             0.        0.28                0.
lateral_visc:   VISC2     [m^2/sec ]
                 1000.  0.
tracer_diff2: TNU2           [m^2/sec]
                 1000. 0.
```

Homework

- For next time:
  - Read https://www.jgula.fr/ModNum/Stommel48.pdf
  - Read https://www.jgula.fr/ModNum/Munk50.pdf
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