CROCO – Training Barcelonnette 2023

Physical parameterizations

CROCO
Coastal and Regional Ocean COmmunity model

Reynolds averaged Primitive Equations

Coastal and Regional Ocean COmmunity model

$$
\begin{aligned}
\frac{D\langle \mathbf{u}_h \rangle}{Dt} + f\mathbf{k}\times\langle \mathbf{u}_h \rangle &= \frac{\boldsymbol{\nabla}_h p}{\rho_0} - \boldsymbol{\nabla}\cdot\langle \mathbf{u}_h'\mathbf{u}_h' \rangle - \partial_z \langle w'\mathbf{u}_h' \rangle \\
\partial_z p &= -g\rho' \\
\boldsymbol{\nabla}\cdot\langle \mathbf{u} \rangle &= 0 \\
\frac{D\langle T \rangle}{Dt} &= -\frac{\partial_z Q_s}{\rho_0 C_{p,o}} - \boldsymbol{\nabla}_h\cdot\langle \mathbf{u}_h' T' \rangle - \partial_z \langle w'T' \rangle \\
\frac{D\langle S \rangle}{Dt} &= -\boldsymbol{\nabla}_h\cdot\langle \mathbf{u}_h' S' \rangle - \partial_z \langle w'S' \rangle \\
\rho &= \rho_{\mathrm{eos}}(\langle T \rangle, \langle S \rangle, z)
\end{aligned}
$$

turbulence effects are classically modelled as enhancing interior mixing and mediating boundary forcing

Physical parameterizations

Coastal and Regional Ocean COmmunity model

- Surface forcing

$$-\langle \mathbf{u}_h' w' \rangle_{\text{sfc}} = \boldsymbol{\tau}/\rho_o$$
$$-\langle T' w' \rangle_{\text{sfc}} = Q_H/(\rho_o C_{p,o})$$

- Interior mixing

$$-\left\langle \mathbf{u}_h' w' \right\rangle(z) = K_m(z)\partial_z \left\langle \mathbf{u}_h \right\rangle$$
$$-\left\langle T' w' \right\rangle(z) = K_s(z)\partial_z \left\langle T \right\rangle$$

- Bottom forcing

$$-\langle \mathbf{u}_h' w' \rangle_{\text{bot}} = \boldsymbol{\tau}_b/\rho_o$$
$$-\langle T' w' \rangle_{\text{bot}} = 0$$

Physical parameterizations

- Surface forcing

$$
\begin{aligned}
-\langle \mathbf{u}_h' w' \rangle_{\rm sfc} &= \boldsymbol{\tau}/\rho_o \\
-\langle T' w' \rangle_{\rm sfc} &= Q_H/(\rho_o C_{p,o})
\end{aligned}
$$

=> directly read forcing files with (heat, freshwater, and momentum flux)
=> or use bulk parameterizations

$$
-\langle \mathbf{u}_h' w' \rangle_{\rm sfc} = C_D \|\Delta \mathbf{u}\| \Delta \mathbf{u}, \qquad \Delta \mathbf{u} = \mathbf{u}_{\rm air} - \mathbf{u}_{k=N}
$$

$$
-\langle T' w' \rangle_{\rm sfc} = C_H \|\Delta \mathbf{u}\| \Delta T, \qquad \Delta T = T_{\rm air} - T_{k=N}
$$

BULK_FLUX	Activate bulk formulation for surface turbulent fluxes (by default, COARE3p0 parametrizarion is used)
BULK_ECUMEV0	Use ECUMEv0 bulk formulation instead of COARE3p0 formulation
BULK_ECUMEV6	Use ECUMEv6 bulk formulation instead of COARE3p0 formulation
BULK_WASP	Use WASP bulk formulation instead of COARE3p0 formulation

Physical parameterizations

- Surface forcing
$$
\begin{aligned}
-\langle \mathbf{u}'_h w' \rangle_{\rm sfc} &= \boldsymbol{\tau}/\rho_o \\
-\langle T' w' \rangle_{\rm sfc} &= Q_H/(\rho_o C_{p,o})
\end{aligned}
$$

=> COARE bulk
$$\|\boldsymbol{\tau}\|/\rho_a = u_\star^2$$
$$Q_H/(\rho_a C_{p,a}) = u_\star \theta_\star$$

$$
\begin{aligned}
\langle u(z)\rangle - \langle u(z_{0,m})\rangle &= u_\star \kappa^{-1}\left[\ln\left(\frac{z}{z_{0,m}}\right) + \psi_m\left(\frac{z}{L_{\rm MO}}\right)\right] \\
\langle \theta(z)\rangle - \langle \theta(z_{0,h})\rangle &= \theta_\star \kappa^{-1}\left[\ln\left(\frac{z}{z_{0,h}}\right) - \psi_s\left(\frac{z}{L_{\rm MO}}\right)\right]
\end{aligned}
$$

$L_{\rm MO} = L_{\rm MO}(u_\star, \theta_\star)$ non-linear system iteratively solved

=> CROCO implementation assumes that the wind speed data are at 10 m, relative or specific humidity at 2 m.

Physical parameterizations

CROCO
Coastal and Regional Ocean COmmunity model

- Surface forcing

$$-\langle \mathbf{u}_h' w' \rangle_{\text{sfc}} = \boldsymbol{\tau}/\rho_o$$
$$-\langle T' w' \rangle_{\text{sfc}} = Q_H/(\rho_o C_{p,o})$$

=> additional functionalities

BULK_GUSTINESS	Add in gustiness effect on surface wind module. Can be used for both bulk parametrizations.
BULK_LW	Add in long-wave radiation feedback from model SST
SFLUX_CFB	Activate current feedback on ... (Renault et al., 2020)
CFB_STRESS	... surface stress (used by default when SFLUX_CFB is defined)
CFB_WIND_TRA	... surface tracers (used by default when SFLUX_CFB is defined)
SST_SKIN	Activate skin sst computation (Zeng & Beljaars, 2005)

QCORRECTION	Activate heat flux correction around model SST (if BULK_FLUX is undefined)
SFLX_CORR	Activate freshwater flux correction around model SSS (if BULK_FLUX is undefined)
ANA_DIURNAL_SW	Activate analytical diurnal modulation of short wave radiations (only appropriate if there is no diurnal cycle in data)

Physical parameterizations

- Bottom forcing
$$-\langle \mathbf{u}_h' w' \rangle_{\text{bot}} = \boldsymbol{\tau}_b/\rho_o$$
$$-\langle T' w' \rangle_{\text{bot}} = 0$$

=> specified in **croco.in**

```
bottom_drag:     RDRG [m/s],  RDRG2,  Zob [m],  Cdb_min, Cdb_max
                 3.0d-04      0.d-3   0.d-3     1.d-4    1.d-1
```

=> quadratic drag with log-layer (if Zob !=0)

$$\boldsymbol{\tau}_b = C_d \|\mathbf{u}_{k=1}\| \mathbf{u}_{k=1}, \qquad C_d = \left(\frac{\kappa}{\ln\left([z_1 - H]/z_{0,b}\right)} \right)^2$$

=> quadratic drag with Cd = cst (if RDRG2 > 0)

$$\boldsymbol{\tau}_b = r_{\text{drg2}} \|\mathbf{u}_{k=1}\| \mathbf{u}_{k=1}$$

=> linear drag (RDRG)

$$\boldsymbol{\tau}_b = r_{\text{drg}} \mathbf{u}_{k=1}$$

Physical parameterizations

- Bottom forcing

$$-\langle \mathbf{u}_h' w' \rangle_{\text{bot}} = \boldsymbol{\tau}_b / \rho_o$$
$$-\langle T' w' \rangle_{\text{bot}} = 0$$

=> specified in **croco.in**

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bottom_drag:     RDRG [m/s],  RDRG2,  Zob [m],  Cdb_min, Cdb_max
                 3.0d-04      0.d-3   0.d-3     1.d-4    1.d-1
```

=> additional functionalities

LIMIT_BSTRESS	Bottom stress limitation forstability
BSTRESS_FAST	Bottom stress computed in step3d_fast
BBL	Bottom boundary layer parametrization

Physical parameterizations

- Interior mixing

$$
\begin{aligned}
-\langle \mathbf{u}_h' w' \rangle (z) &= K_m(z)\partial_z \langle \mathbf{u}_h \rangle \\
-\langle T' w' \rangle (z) &= K_s(z)\partial_z \langle T \rangle
\end{aligned}
$$

Available options :

ANA_VMIX	Analytical definition
BVF_MIXING	Brunt-Vaisaleafrequency based
LMD_MIXING	K-profile parametrisation
GLS_MIXING	Generic lengthscale parametrisation

ANA_VMIX, BVF_MIXING: simple parameterizations for idealized studies

LMD_MIXING, GLS_MIXING: more advanced parameterizations for realistic cases

Physical parameterizations

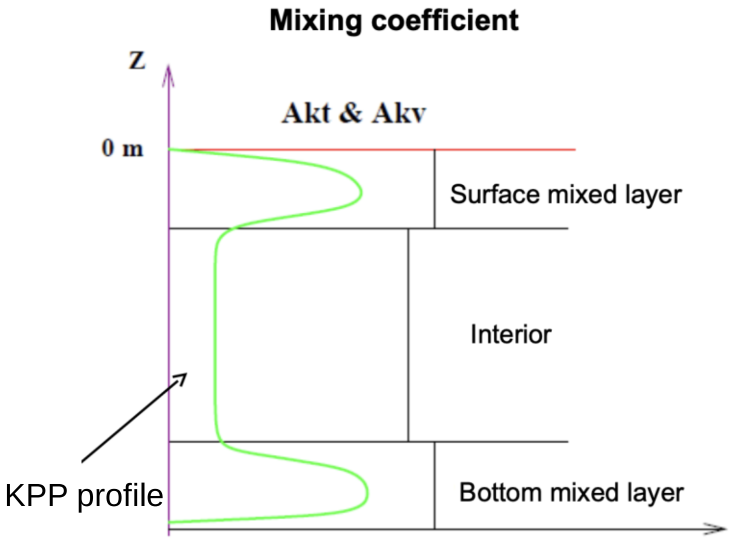
- Interior mixing

$$-\langle \mathbf{u}'_h w' \rangle (z) = K_m(z)\partial_z \langle \mathbf{u}_h \rangle$$
$$-\langle T' w' \rangle (z) = K_s(z)\partial_z \langle T \rangle$$

K-profile parameterization (KPP) :

KPP-related options

LMD_MIXING	K-profile parametrisation
LMD_SKPP	Activate surface boundary layer KPP mixing
LMD_SKPP2005	Activate surface boundary layer KPP mixing (2005 version)
LMD_BKPP	Activate bottom boundary layer KPP mixing
LMD_BKPP2005	Activate bottom boundary layer KPP mixing (2005 version)
LMD_RIMIX	Activate shear instability interior mixing
LMD_CONVEC	Activate convection interior mixing
LMD_DDMIX	Activate double diffusion interior mixing
LMD_NONLOCAL	Activate nonlocal transport for SKPP
LMD_LANGMUIR	Activate Langmuir turbulence mixing



Physical parameterizations

- Interior mixing

$$-\left\langle \mathbf{u}'_h w' \right\rangle (z) = K_m(z)\partial_z \left\langle \mathbf{u}_h \right\rangle$$
$$-\left\langle T' w' \right\rangle (z) = K_s(z)\partial_z \left\langle T \right\rangle$$

K-profile parameterization (KPP) :

Surface boundary layer

LMD_SKPP (Large et al, 1994)

Step 1 : Compute boundary layer depth $h_{bl}(z_r \to z_N)$

$$\mathrm{Ri}_b(z) = \frac{g(z_r - z)\left(\rho(z) - \rho_r\right)/\rho_0}{|\mathbf{u}(z) - (\mathbf{u}_h)_r|^2 + V_t^2(z)}, \qquad \mathrm{Ri}_b(-h_{bl}) = \mathrm{Ri}_{cr} \qquad \mathrm{Ri}_{cr} \in [0.15, 0.45]$$

Step 2 : In the stable case math::(B_f > 0) : h_{bl} = min(h_{bl}, h_{ek}, h_{mo})

$$h_{ek} = 0.7 u_\star / f, \qquad h_{mo} = u_\star^3 / (\kappa B_f).$$

step 3 : Compute turbulent viscosity and diffusivity

$$K_{m,s}(z) = w_{m,s}\, h_{bl}\, G(z/h_{bl}), \qquad w_{m,s} = \kappa\, u_\star\, \psi_{m,s}(z B_f / u_\star^3)$$

Physical parameterizations

- Interior mixing

$$\begin{aligned} -\langle \mathbf{u}_h' w' \rangle (z) &= K_m(z)\partial_z \langle \mathbf{u}_h \rangle \\ -\langle T' w' \rangle (z) &= K_s(z)\partial_z \langle T \rangle \end{aligned}$$

K-profile parameterization (KPP) :

Surface boundary layer

LMD_SKPP2005 (Shchepetkin et al, 2005)

Criteria for h_{bl} : integral layer where production of turbulence by shear balances dissipation by the stratification

$$\mathrm{Cr}(z) = \int_z^{\zeta} \mathcal{K}(z') \left\{ |\partial_{z'} \mathbf{u}_h|^2 - \frac{N^2}{\mathrm{Ri}_{cr}} - C_{Ek}\, f^2 \right\} dz' + \frac{V_t^2(z)}{(\zeta - z)}, \ \mathrm{Cr}(-h_{bl}) = 0$$

Consistent with the original KPP

Advantages :
-> consistent with Ekman problem
-> tends to give deeper boundary layers : $(\zeta - z) \int_z^{\zeta} |\partial_{z'} \mathbf{u}_h|^2 dz' \geq |\mathbf{u}_h(z) - \mathbf{u}_h(\zeta)|^2$.

Physical parameterizations

- Interior mixing
$$-\langle \mathbf{u}'_h w' \rangle (z) = K_m(z)\partial_z \langle \mathbf{u}_h \rangle$$
$$-\langle T' w' \rangle (z) = K_s(z)\partial_z \langle T \rangle$$

K-profile parameterization (KPP) :

Interior scheme

$$K_{m,s}(z) = K^{\mathrm{sh}}_{m,s}(z) + K^{\mathrm{iw}}_{m,s}(z) + K^{\mathrm{dd}}_{m,s}(z)$$

cpp key LMD_RIMIX, RI_(H-V)SMOOTH (Large et al., 1994)

$$\mathrm{Ri}_g = N^2 / \left[(\partial_z u)^2 + (\partial_z v)^2\right]$$

$$K^{\mathrm{sh}}_{m,s}(z) = \begin{cases} K_{0,c} & \mathrm{Ri}_g < 0 \quad \leftarrow \text{[LMD\_CONVEC]} \\ K_0 \left[1 - \left(\frac{\mathrm{Ri}_g}{\mathrm{Ri}_0}\right)^3\right] & 0 < \mathrm{Ri}_g < \mathrm{Ri}_0 \\ 0 & \mathrm{Ri}_0 < \mathrm{Ri}_g \end{cases}$$

$$K_0 = 5 \times 10^{-3}\ \mathrm{m^2\ s^{-1}}, \mathrm{Ri}_0 = 0.7$$

Physical parameterizations

- Interior mixing
$$-\langle \mathbf{u}'_h w' \rangle (z) = K_m(z)\partial_z \langle \mathbf{u}_h \rangle$$
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K-profile parameterization (KPP) :

Interior scheme

$$K_{m,s}(z) = K^{\mathrm{sh}}_{m,s}(z) + K^{\mathrm{iw}}_{m,s}(z) + K^{\mathrm{dd}}_{m,s}(z)$$

cpp key LMD_NUW_GARGETT (Gargett & Holloway)

$$K^{\mathrm{iw}}_m(z) = \frac{10^{-6}}{\sqrt{\max(N^2(z), 10^{-7})}}, \qquad K^{\mathrm{iw}}_s(z) = \frac{10^{-7}}{\sqrt{\max(N^2(z), 10^{-7})}}$$

cpp key LMD_DDMIX (cf Large et al., 1994, eqns (31))

Physical parameterizations

Coastal and Regional Ocean COmmunity model

- Interior mixing
$$
\begin{aligned}
-\left\langle \mathbf{u}_h' w' \right\rangle (z) &= K_m(z) \partial_z \left\langle \mathbf{u}_h \right\rangle \\
-\left\langle T' w' \right\rangle (z) &= K_s(z) \partial_z \left\langle T \right\rangle
\end{aligned}
$$

K-profile parameterization (KPP) :

Bottom boundary layer

cpp key LMD_BKPP (Bottom KPP 1994)

Same rationale than surface KPP but this time we search for the critical value $\mathrm{Ri}_{\mathrm{cr}}$ (≈ 0.3) starting from the bottom

$$
h_{\mathrm{bbl}} = \min\left(h_{\mathrm{bbl}}, \frac{0.7 u_{\star,b}}{|f|} \right) K_{m,s}(z) = \kappa\, u_{\star,b}\, h_{bbl}\, G(\sigma), \qquad \sigma = \frac{(z-h)}{h_{bbl}}
$$

Physical parameterizations

- Interior mixing

$$-\langle \mathbf{u}'_h w' \rangle (z) = K_m(z)\partial_z \langle \mathbf{u}_h \rangle$$
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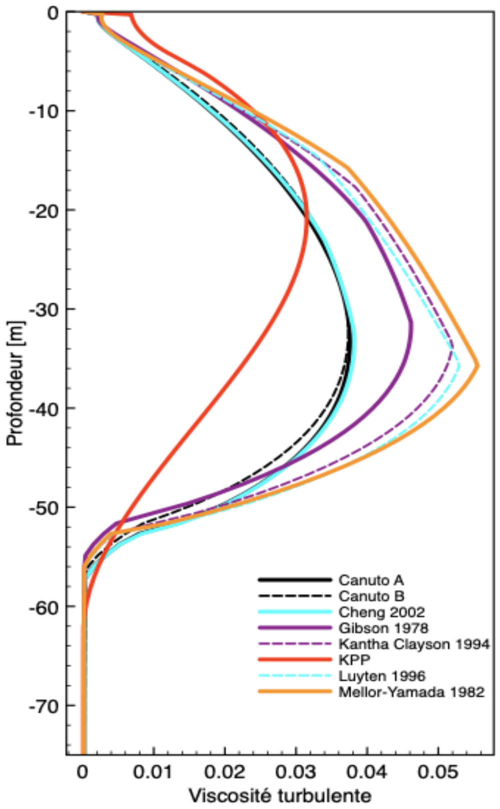
Generic length-scale parameterization (GLS) :

GLS_MIXING	Activate Generic Length Scale scheme, default is k-epsilon (see below)
GLS_KOMEGA	Activate K-OMEGA (OMEGA=frequency of TKE dissipation)
GLS_KEPSILON	Activate K-EPSILON (EPSILON=TKE dissipation)
GLS_GEN	Activate generic model of Umlauf and Burchard (2003)
CANUTO_A	Option for CANUTO A stability function (default, see below)
GibLau_78	Option for Gibson & Launder, 1978 stability function
MelYam_82	Option for Mellor & Yamada, 1982 stability function
KanCla_94	Option for Kantha & Clayson, 1994 stability function
Luyten_96	Option for Luyten, 1996 stability function
CANUTO_B	Option for CANUTO B stability function
Cheng_02	Option for Cheng, 2002 stability function



Physical parameterizations

Coastal and Regional Ocean COmmunity model

- Interior mixing

$$
\begin{aligned}
-\left\langle \mathbf{u}'_h w' \right\rangle (z) &= K_m(z)\partial_z \left\langle \mathbf{u}_h \right\rangle \\
-\left\langle T' w' \right\rangle (z) &= K_s(z)\partial_z \left\langle T \right\rangle
\end{aligned}
$$

KPP or GLS…?

=> Advices for choosing:

- KPP assumes that turbulence in the boundary layer is in equilibrium with surface and bottom fluxes => true for large scale models
- GLS models explicitly treat temporal high frequency in the BL, role of horizontal terms in TKE equation almost not studied…
- For coastal applications, the scheme should : respond to local forcing, respond rapidly to surface and bottom fluxes => GLS-type scheme preferred

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For more details

https://croco-ocean.gitlabpages.inria.fr/croco_doc/index.html