SEDIMENT DYNAMICS
Introduction to sedimentary modeling and to MUSTANG module

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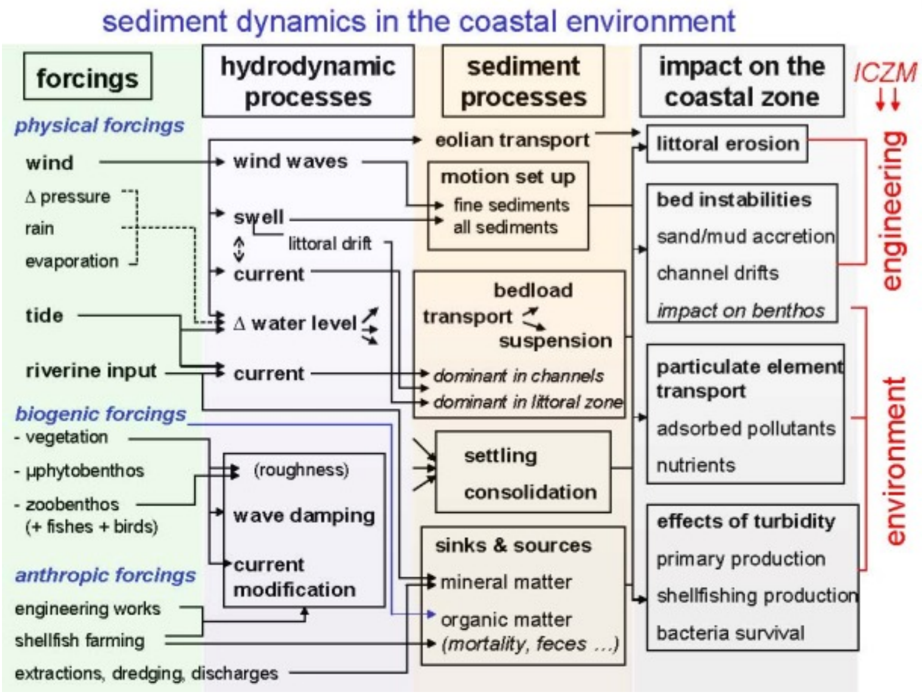
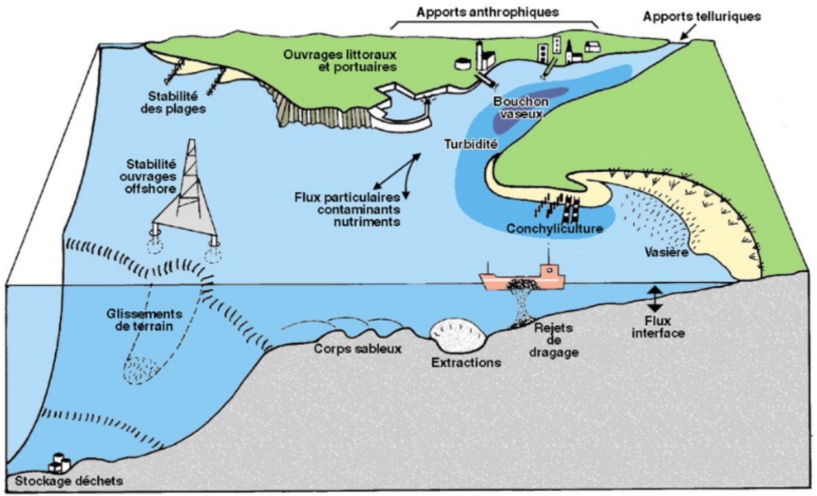
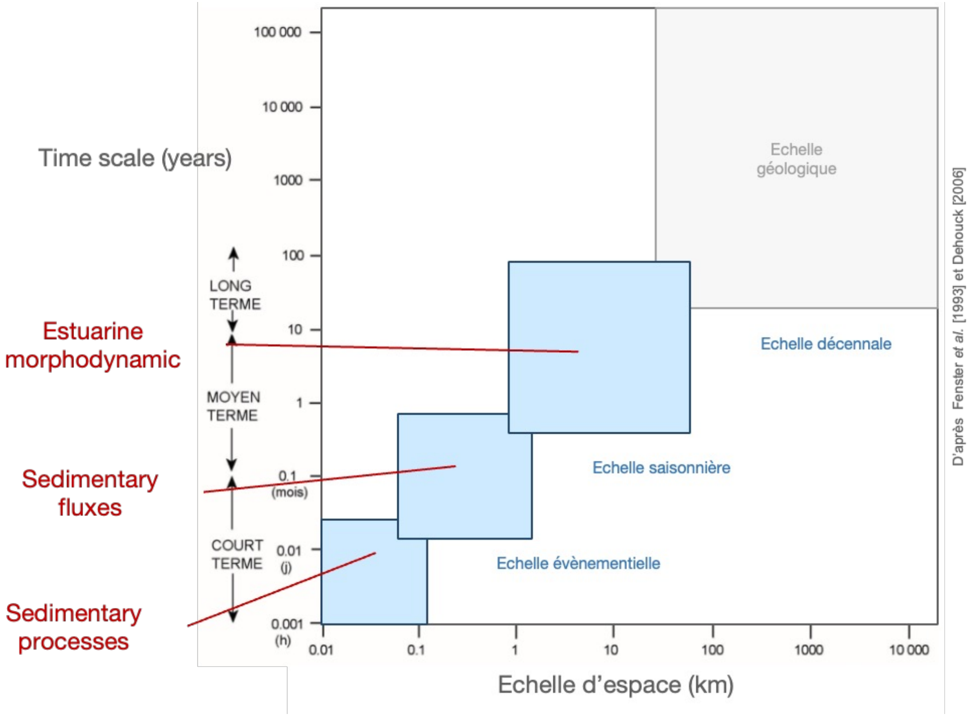
Introduction



Introduction





Outline

- **Sedimentary modeling in general**
  - Forcing drivers
  - Sediment properties and behaviors
  - Modes of sediment transport
  - Modeling strategies, sediment modules in CROCO

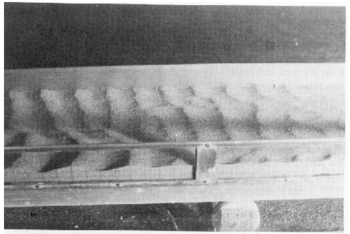
- **MUSTANG**
  - Main processes and formulations
  - Implementation, global structure
  - Input files and parameters, main options
  - Perspectives

- **Some examples**
  - CROCO/MUSTANG – Bay of Biscay
  - CROCO/MUSTANG – Seine estuary

Forcing drivers

- **Roughness length**

  Distinguish grain (Nikuradse formula) or form related (ripple bed roughness : Grant and Madsen, Van Rijn, Wiberg and Rubin)



➡ Use skin friction with roughness length depending on bed composition
Z0sed $\neq$ Z0hydro

- **Current and wave shear stress**

  Interaction between current and wave

$$\tau_c = \frac{\kappa^2}{\ln^2(z/z_0)}|u|^2$$

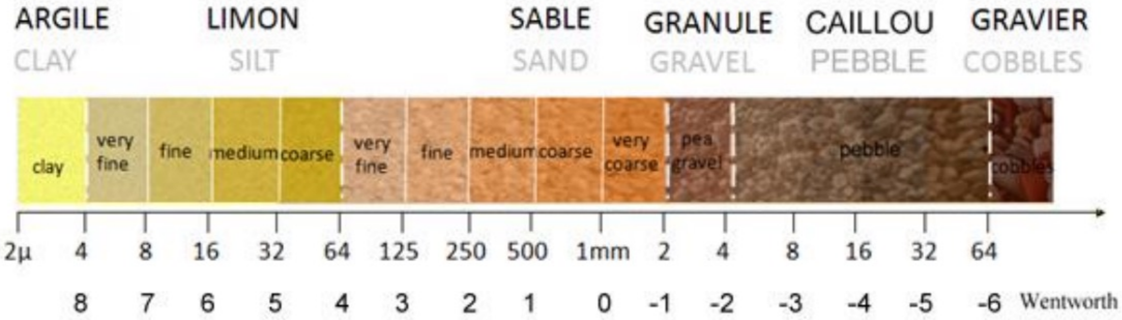
$$\tau_w = 0.5\rho f_w u_b^2$$

$$\bar{\tau}_{wc} = \tau_c \left(1 + 1.2\left(\frac{\tau_w}{\tau_w + \tau_c}\right)^{3.2}\right)$$

➡ Combination of shear stresses
Needs to know hydrodynamic variables : depth, current, wave period, wave orbital velocity, water density, bed roughness length

Sediment properties

- Sediment can be characterized by grain size (d50, d90)



- **cohesive** : mud (clay, silt)
  - transport in suspension
  - flocculation, variable settling velocities
  - bed consolidation
- **non cohesive** : sand to cobble
  - transport in suspension and/or bedload

Sediment properties – settling velocity

Cohesive

Stokes if isolated grains

Links between grains leads to variable settling velocities (flocculation, hindered effect)

→ Several formulations (Migniot, Thorn & Parsons, Van Leussen) or modeling approaches (Winterwerp, Wolanski)

Non cohesive

No link between grains
Hindered effect with high concentration

Wide range of values
~1 cm/s for ~100 μm grain size
~10 cm/s for ~800 μm grain size

Soulsby (1997)

$$W_s = \frac{\nu}{D}\left[(10.36^2 + 1.049 D_*^3)^{0,5} - 10.36\right] \quad \text{avec } D_* = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

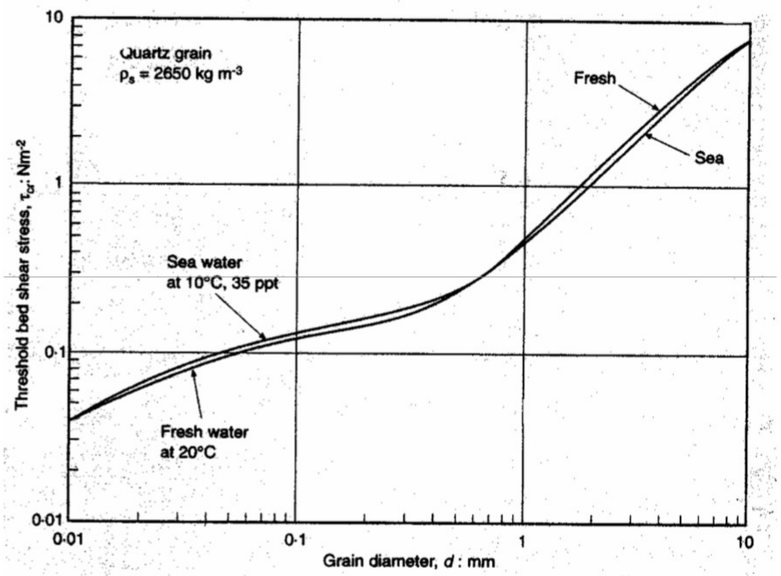
Sediment properties – motion threshold

Cohesive

Depends on consolidation and cohesion of sea bed

Non cohesive

Depends mainly on grain diameter



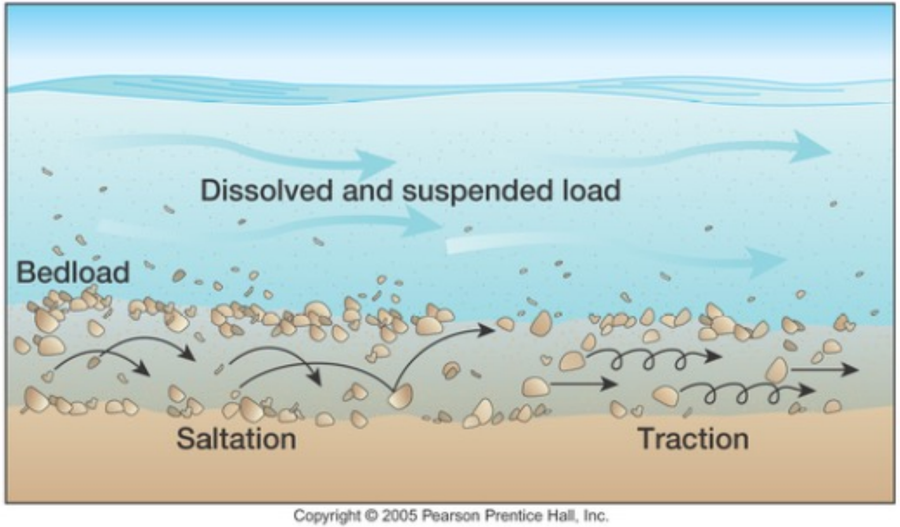
$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055\left[1 - \exp(-0.02\,D_*)\right]$$

BEDLOAD

Transport in contact with the bed : rolling, saltation

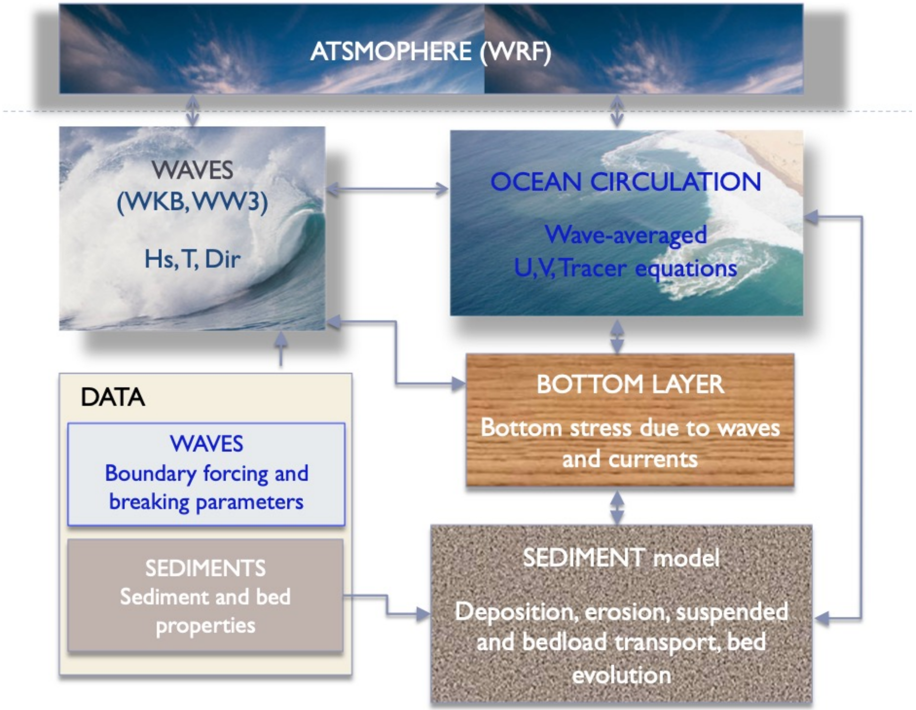
SUSPENSION

Transport in water



All simultaneously

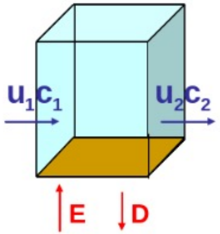
Modelling strategies



Modelling strategies

Non-equilibrium transport
Erosion-deposition fluxes

suspension:
$u_{part.} = u_{eau}$



Erosion flux : ***E = f(cond. Hydro., param. Sed.)***

Deposition flux: $D = W_s C(1 - \frac{\tau}{\tau_d})$

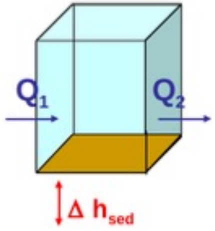
Eq. Advection/dispersion:

$$\frac{\partial hC}{\partial t} + \frac{\partial hUC}{\partial x} = E - D$$

Bottom evolution: $\frac{\partial h_{sed}}{\partial t} = \frac{1}{C_{sed}}(D - E)$

Transport at equilibrium
Many formulas available

Current only, current and wave
Wave asymmetry, slope effect



Transport at equilibrium :
« transport capacity»

Q = f(cond. Hydro., param. Sed.)

Bottom evolution:

$$(1 - p)\frac{\partial h_{sed}}{\partial t} = \frac{\partial Q}{\partial x}$$

Sediment modules in CROCO

2 models available :

USGS model : cpp key **#SEDIMENT**

- « legacy » model
- originally included in ROMS-AGRIF
- available in ROMS-RUTGERS and OAWST

IFREMER model : cpp key **#MUSTANG**

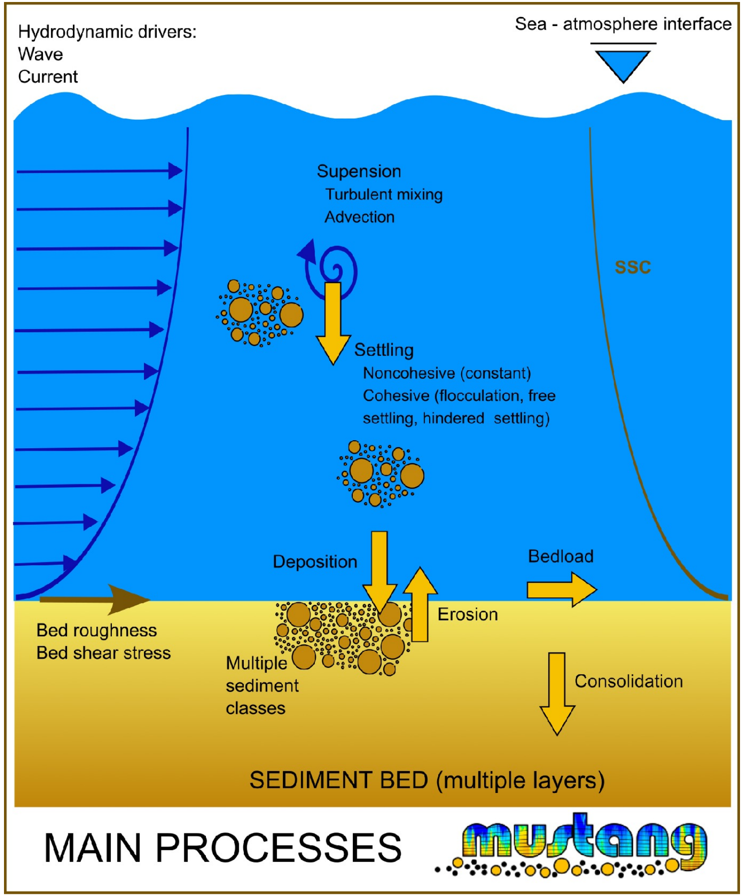
- french model
- originally included in MARS3D
- available since 1.2 (released Jan 2022)

MUSTANG

MUd and **S**and **T**r**AN**sport modellin**G**

Developed at IFREMER by P.Le Hir, in SiAM, then MARS3D and now available in CROCO (since 1.2)

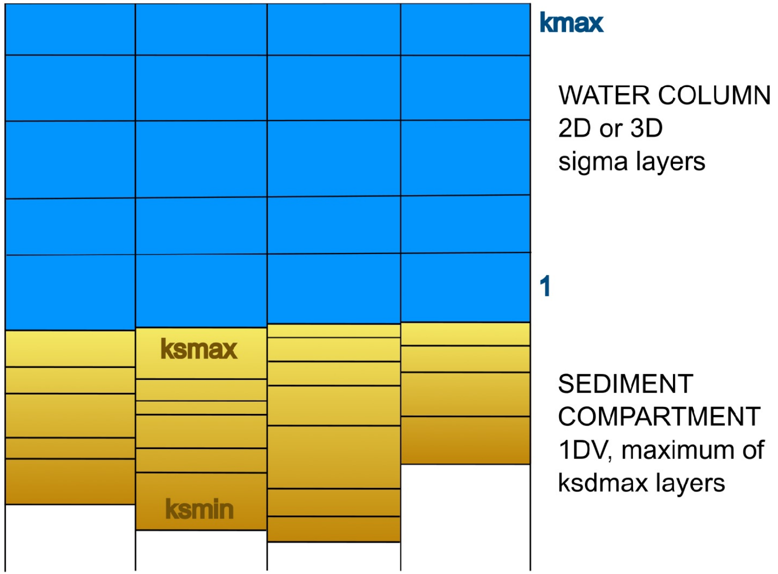
Always coupled with an hydrodynamic model !
In CROCO activated by cppkey #MUSTANG



MUSTANG – sediment type and sediment grid

Use sediment classes
3 types of sediment

Type	Bedload transport	Transport in suspension	Flocculation
MUD	NO	YES	YES
SAND	YES	YES	NO
GRAVEL	YES	NO	NO



Horizontal exchange at sediment/water interface, no horizontal exchange in sediment bed

MUSTANG - implementation main steps

Erosion phase
Update z0
Update τ
Compute erosion fluxes
Compute bedload fluxes
Erosion bed layer management
Trend of deposit fluxes

Exchange water/sediment
including E/D fluxes and settling

Deposit phase
Update deposit fluxes
Deposit bed layer management

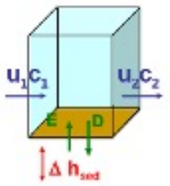
Morphodynamic coupling

Advection part : for each class of sediment adding erosion/deposition fluxes

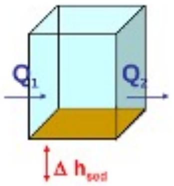
$$\underbrace{\frac{\partial C}{\partial t}}_{RATE} = -\underbrace{\vec{\nabla}.\vec{v}C}_{ADVECTION} + \underbrace{\mathcal{D}_C}_{MIXING} - \underbrace{\frac{\partial w_s C}{\partial z}}_{SETTLING} + \underbrace{\left.\frac{E}{\delta z_b}\right|_{z=z_b}}_{EROSION}$$

Erosion = f(τ_s,τ_e,bed composition)
Deposit = Ws . f(τ_s,τ_d) . Cbot_extrap
Ws = f(C, turbulence, salinity)
τ_e = f(consolidation)

Evolution of sediment height



- Exchange water-sediment + advection
- Erosion fluxes from sediment bed
- Multiclass interactions



- Wu & Lin 2014
- Slope effect from Lesser 2004
- Multiclass interactions

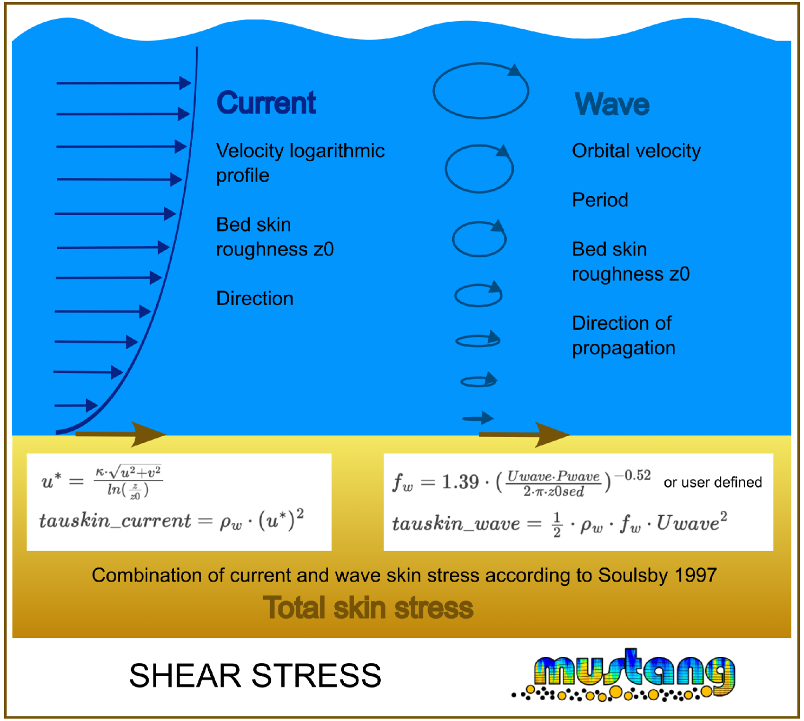
MUSTANG
Roughness length and bed shear stress

Roughness length :

- Z0sed : constant (**l_z0seduni** = .TRUE.) ,or diam/12 with diam f(bed composition)
- Z0hydro : possibility to compute roughness length from bed composition for coupling with roughness in hydrodynamic part

Skin friction :

- Current part (with options to compute current at the center of the cell)
- Wave part if #WAVE_OFFLINE
- Combination (Soulsby 1997)



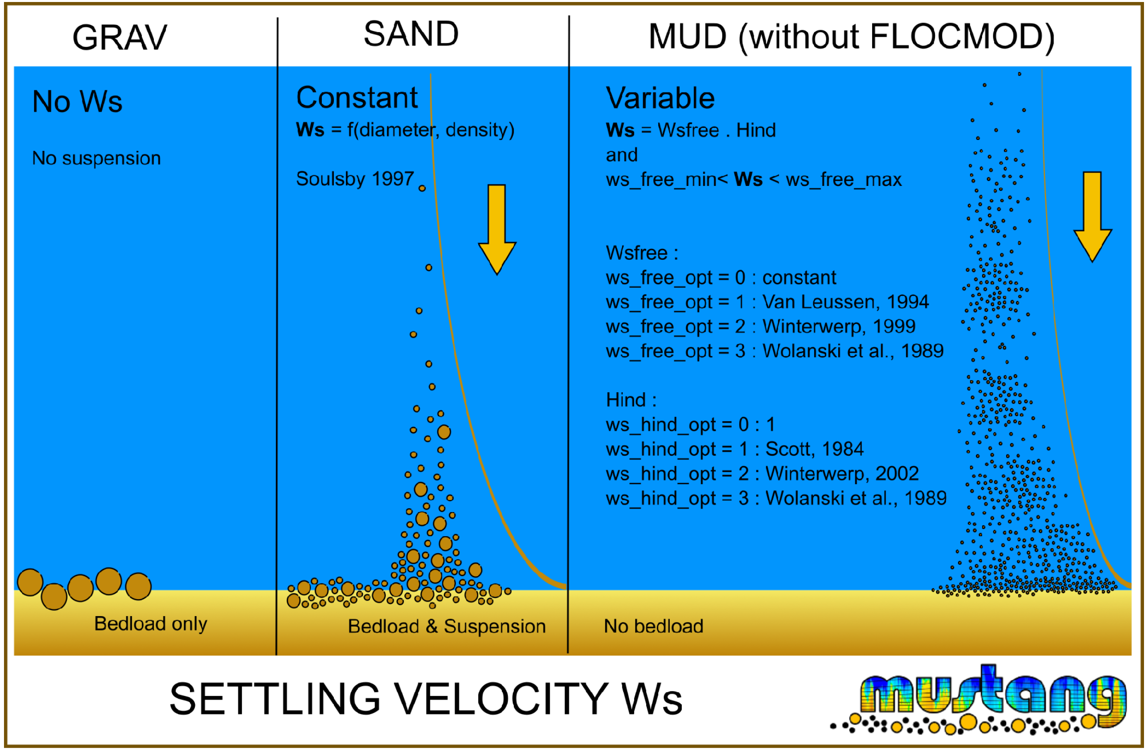
If cppkey **#WAVE_OFFLINE**

MUSTANG
Settling velocity

$$\underbrace{\frac{\partial C}{\partial t}}_{RATE} = -\underbrace{\vec{\nabla}.\vec{\mathbf{v}}C}_{ADVECTION} + \underbrace{\mathcal{D}_C}_{MIXING} - \underbrace{\frac{\partial w_s C}{\partial z}}_{SETTLING} + \underbrace{\frac{E}{\delta z_b}\Big|_{z=z_b}}_{EROSION}$$

- sink term
- constant or variable (depends of sediment type and input parameters)

Vertical advection :
sub time step to treat settling
(explicit upwind scheme order 1)



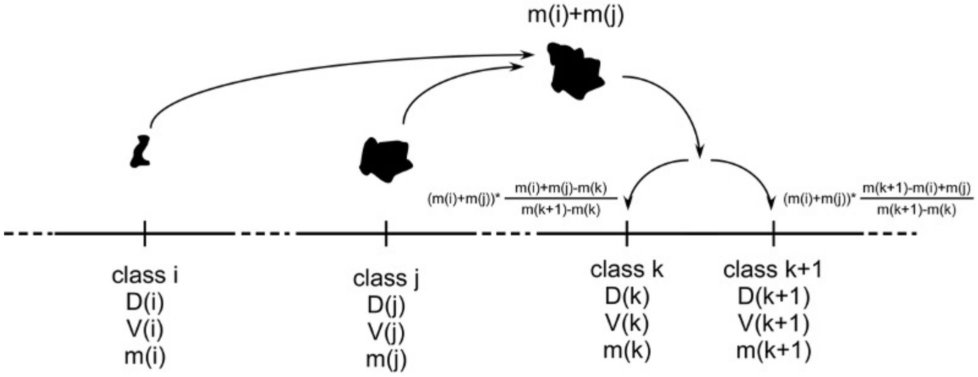
MUSTANG
Settling velocity with flocculation explicitly modelled

FLOCMOD

https://croco-ocean.gitlabpages.inria.fr/croco_doc/model/model.modules.sediment_mustang.html#flocculation-with-flocmod
https://croco-ocean.gitlabpages.inria.fr/croco_doc/model/model.test_cases.sediment.html
(3. **FLOCMOD cases : #SED_TOY_FLOC_0D and #SED_TOY_FLOC_1D**)

0D size-class-based module developed by Ifremer to simulate the explicitly flocculation processes (See Verney et al., 2011)

Distribution of MUD mass on all the flocs classes using a fractal approach and 5 processes (shear aggregation, differential settling aggregation, shear fragmentation, shear erosion, shear collision)



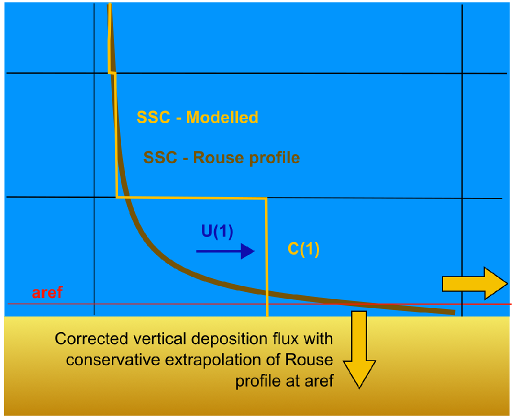
WARNING : cost in CPU time

MUSTANG
SAND type – high Ws

Corrections added :

- deposit from an extrapolated concentration at aref location
- horizontal fluxes corrected in the bottom layer to take into account both velocity and concentration gradients close to the bottom => only if **#MUSTANG_CORFLUX**

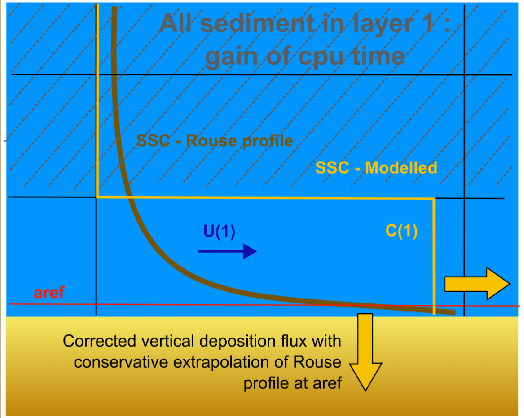
+ Gain in CPU time with #key_sand2D



#MUSTANG_CORFLUX
Horizontal advection fluxes correction factor considering a Rouse profile of concentration and a logarithmic profile of current :

$$\text{corflux} = \frac{\int_{aref}^{zw(1)} C_{rouse}\ u_{log}\ dz}{u(1)C(1)\Delta z(1)}$$

SAND suspension corrections in 3D



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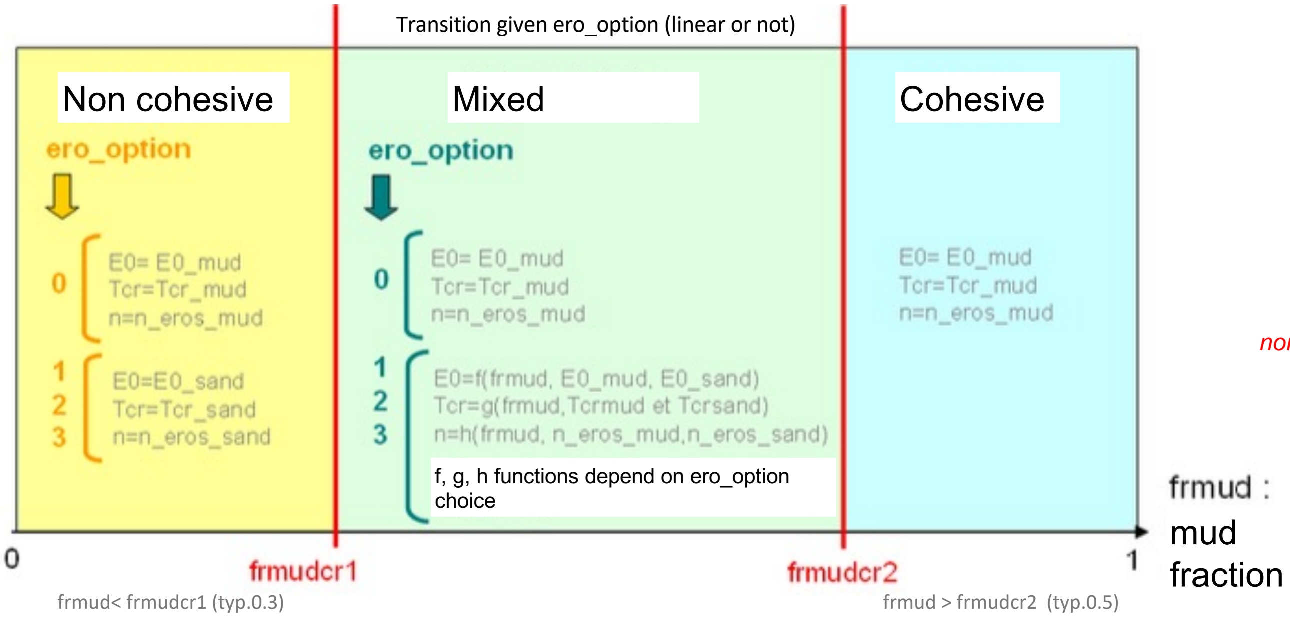
$$\text{corflux} = \frac{\int_{aref}^{zw(1)} C_{rouse}\ u_{log}\ dz}{u(1)C(1)\Delta z(1)}$$

SAND suspension corrections with **#key_sand2D**

MUSTANG – Erosion fluxes

In « V1 » (#undef key_MUSTANG_V2)



$$E = E_0 \left(\frac{\tau - \tau_c}{\tau_c} \right)^n$$

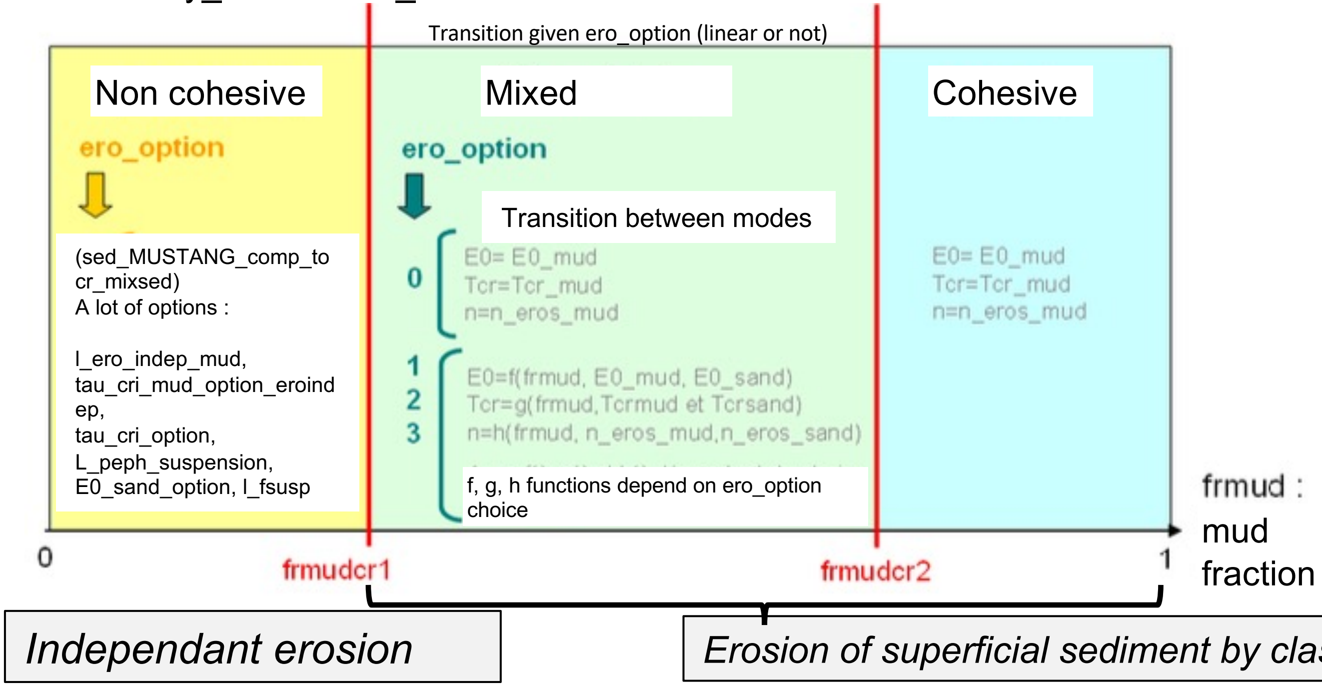
NB :

Erosion of sand not realistic

Continuity of transition between non-cohesive / cohesive / mixed regimes

MUSTANG – Erosion fluxes

With #key_MUSTANG_V2 :



$$E = E_0 \left(\frac{\tau - \tau_c}{\tau_c} \right)^n$$

NB :

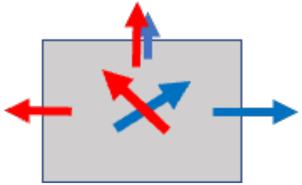
Erosion of sand more realistic

Discontinuity between non-cohesive / cohesive or mixed regimes

MUSTANG – Bedload

Bedload (#key_MUSTANG_V2) : Wu & Lin formulation

- Horizontal fluxes are computed on the direction of shear stress evaluated at center of cell
- Both composants (u,v) are extracted during erosion phase
- Fluxes from adjacent cells are then treated like additional deposit fluxes
- Fluxes are limited with available sediment



$$Q_b = 0.0053 * \left[\frac{\tau}{\tau_{cr}} - 1\right]^{2.2} * \left[(s-1)gD_{50}\right]^{1/2}$$

Slope effect : Lesser et al.

- option : correction of bedload fluxes from bed slope

$$\alpha_s = 1 + \alpha_{bs} \cdot \left(\frac{tan(\phi)}{cos(beta\_s) \cdot (tan(\phi) - tan(beta\_s))} - 1\right)$$
$$qx' = qx \cdot \alpha_s$$
$$qy' = qy \cdot \alpha_s$$
$$\alpha_n = \alpha_{bn} \cdot tan(beta\_n) \cdot \left(\frac{taucr}{tau}\right)^{0.5}$$
$$qx = qx' - qy' \cdot \alpha_n$$
$$qy = qy' + qx' \cdot \alpha_n$$

MUSTANG – Erosion

V1 No bedload

Iterative process over time step

Non cohesive, mixed or cohesive ??

*Erosion of superficial sediment by **class proportion***

update of bed layer with fusion of layer if remaining surface layer is too small

If still time and all layer eroded

V2 (**#key_MUSTANG_V2**)

Iterative process over time step

Non cohesive, mixed or cohesive ??

Indépendant erosion
Combine erosion fluxes and bedload

- compute active layer thickness and mixing
- potential bedload by class
- potential erosion fluxes by class
- limitation by availability
- update layer and porosity

*Erosion of superficial sediment by **class proportion***

update of bed surface layer and porosity

If still time and all layer eroded

MUSTANG – Deposit fluxes

Krone law : $$D_{iv} = W_{s,iv} C_{aref} \left(1 - \frac{\tau_{skin}}{\tau_{d,iv}}\right)$$

With :

MUD
C_{aref} = C (k=1)
τd = f(concentration of fresh deposit)

SAND
C_{aref} = extrapolation of $C_{k=1}$ at elevation *z=aref,*
given a Rouse profile
τd infinity

MUSTANG – Deposit

V1 : Deposition from the coarsest to the finest

- Each class of gravel or sand sediment is in first put in the existing surface layer until *cvolmaxmel* is reached then the resting sediment is put in a new layer.
- For mud sediment, the deposit is made from the surface when a new layer is created by an exceeding of sand or gravel in order to avoid trapping mud sediment by mixing it in the underneath layer ksmax-1 when a new layer is created.
- Possible cases if there is deposition
  - sediment already exist (ksma > 0) :
    - if superficial sediment is not consolidated (cmudr < *cmudcr*) then mixing with superficial sediment until completion (*cvolmaxmel*) before creation of a new layer
    - else : creation of a new layer
  - no existing sediment : creation of a new layer

V2 (**#key_MUSTANG_V2**) : Simultaneous deposition of gravel, sand and mud.

- For each class , deposit is computed from bedload and settling fluxes

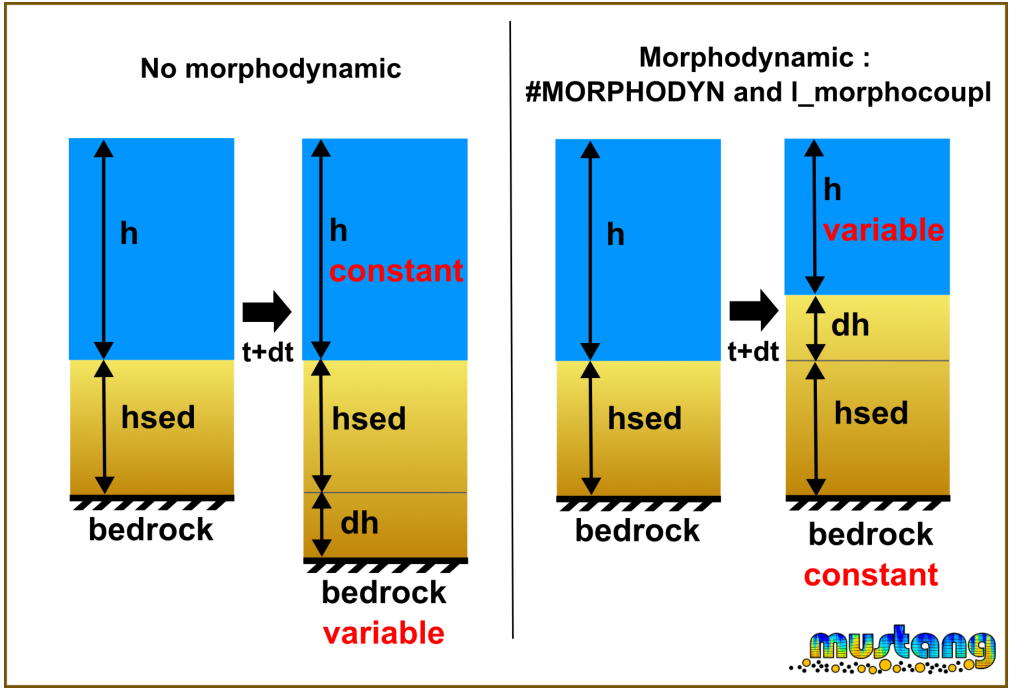
Deposit is different of superficial sediment ? (Density, composition, porosity)

YES → Creation of a new layer

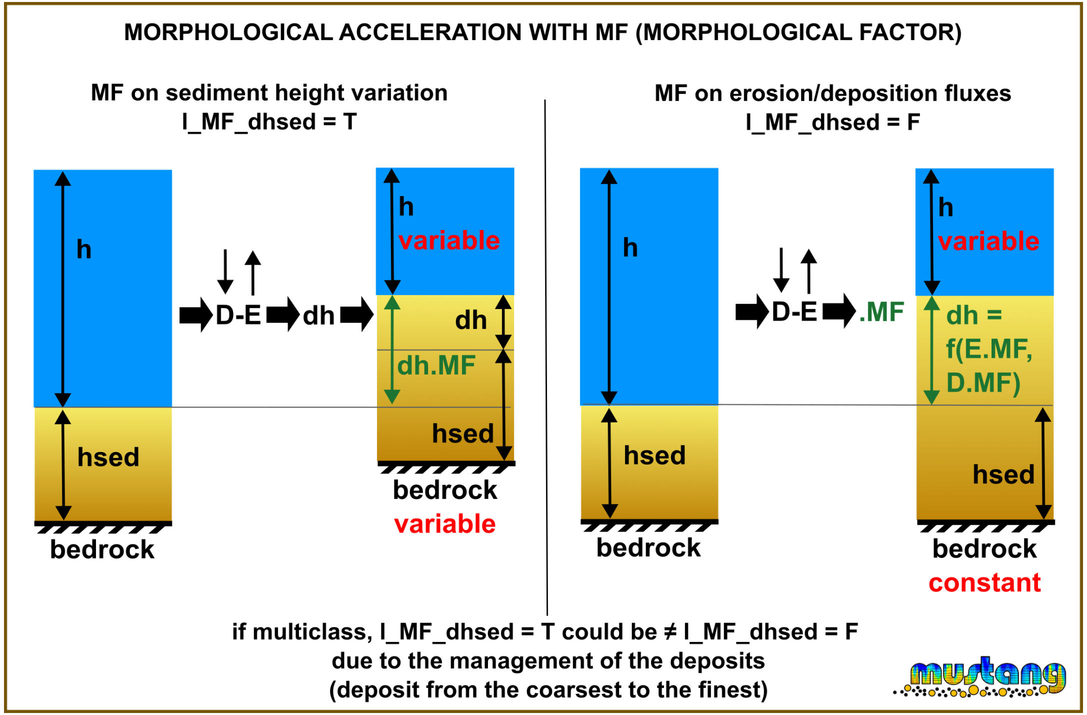
NO → Mixing with the surface layer

Update of porosity

MUSTANG – Morphodynamic



MUSTANG – Morphodynamic - MF



MUSTANG – options and input files

Mustang is controlled through both CPP keys and input files
A lot of parameters and combinations

To use MUSTANG in CROCO :

- **cppdefs.h** >> **#MUSTANG #SUBSTANCE #SALINITY #TEMPERATURE #USE_CALENDAR #key_noTSdiss_insed #key_nofluxwat_IWS** + *option cppkeys*

- **croco.in** >> MUSTANG and SUBSTANCE files

- **param.h** >> add sediment dimensions (classes and bed layers)

- **options : input files** >> initialization file, wave file, source with solid discharge file

MUSTANG – input files

croco.in

```
sediments_mustang: input file
               MUSTANG_NAMELIST/parasubstance.txt
               MUSTANG_NAMELIST/paraMUSTANG.txt
```

Substance namelist >> example MUSTANG_NAMELIST/parasubstance_MUSTANG_full_example.txt

MUSTANG namelist >> default MUSTANG_NAMELIST/paraMUSTANG_default.txt

→ Examples in TESTCASES

MUSTANG – input files

param.h

- **ksdmin & ksdmax** : sediment variables are allocated with ksdim:ksdmax dimension, ksdmin = 1 and ksdmax = number of sediment layers
- **ntrc_subs** : number of substance corresponding to a tracer (advected), sediment are counted in ntrc_subs
- **ntfix** : number of fixed substance (not advected)
- **ntrc_substot** : total number of substance (= ntrc_subs + ntfix)

MUSTANG – input files : parasubstance.txt

- nmlnbvar : number of each type of substance to be defined (other than T (temperature) & S (salinity))
- nmlpartnc : characterization of Non Constitutive Particulate subtances
- nmlpartsorb : characterization of particulate susbtances sorbed on an other particule
- nmlvardiss : characterization of dissolved susbtances
- nmlvarfix :characterization of fixed susbtances (not advected)
- **nmlgravels (if MUSTANG only) : characterization of GRAVEL substances**
- **nmlsands (if MUSTANG only) : characterization of SAND substances**
- **nnmlmuds (if MUSTANG only) : characterization of MUD substances**
- nmlvarbent (if key_benthic only) : characterization of benthic substances

MUSTANG – input files : paraMUSTANG.txt

- namsedim_init : relative to sediment initialization
- namsedim_layer : relative to sediment layers characterization and active layer
- namsedim_bottomstress : relative to bottom shear stress
- namsedim_deposition : relative to sediment deposition
- namsedim_erosion : relative to sediment erosion
- namsedim_poro : relative to porosity (only if key_MUSTANG_V2)
- namsedim_bedload : relative to sediment bedload (only if key_MUSTANG_V2)
- namsedim_lateral_erosion : relative to lateral sediment erosion (only if key_MUSTANG_lateralerosion)
- namsedim_consolidation : relative to sediment consolidation
- namsedim_diffusion : relative to dissolved diffusion in sediment
- namsedim_bioturb : relative to bioturbation in sediment
- namsedim_morpho : relative to morphodynamic
- namtempsed : relative to temperature estimation in sediment (only if !defined key_noTSdiss_insed)
- namsedoutput : parameters used for output results in the file sediment
- namsedim_debug : output for debug (only if key_MUSTANG_debug and key_MUSTANG_V2)
- namflocmod : parameters using for FLOCMOD module (only if key_MUSTANG_flocmod)

MUSTANG – main option cppkeys

key_MUSTANG_V2	to use MUSTANG in V2, without this key, the version V1 is used
MORPHODYN	to activate morphodynamic
key_sand2D	to treat SAND in suspension as 2D variable
MUSTANG_CORFLUX	to correct SAND horizontal fluxes
WAVE_OFFLINE	to use wave in bed shear stress computation
key_tauskin_c_*	options for current-induced bottom shear stress
key_mustang_flocmod	To activate FLOCMOD module
key_MUSTANG_slipdeposit	Add sliding fluxes
key_MUSTANG_lateralerosion	Add lateral erosion process
key_MUSTANG_splitlayersurf	cutting sediment layers to have regular and precise discretization at surface
key_MUSTANG_bedload	only with key_MUSTANG_V2, bedload processus included
key_MUSTANG_debug	only with key_MUSTANG_V2, not MPI compatible, to print information during E/D
key_MUSTANG_specif_outputs	adding output variables in history file

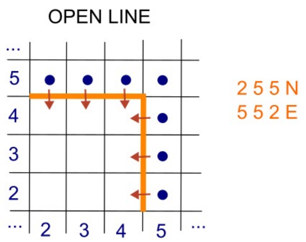
MUSTANG – Perspectives

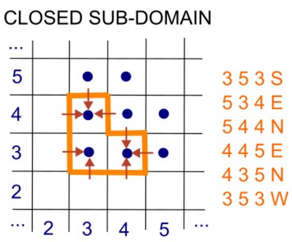
Underway, next release :

- #SED_DENS : to take into account sediment concentration contribution in the water density in the equation of state

$$\rho = \rho_w + \sum_{i=1}^{nvpc} \frac{C_i}{\rho_{s,i}}(\rho_{s,i} - \rho_w)$$

- #SUBSTANCE_SUBMASSBALANCE : This functionnality allows you to compute for each substance : fluxes through boundaries and budgets (stocks and fluxes) in sub-domains





Incoming development :

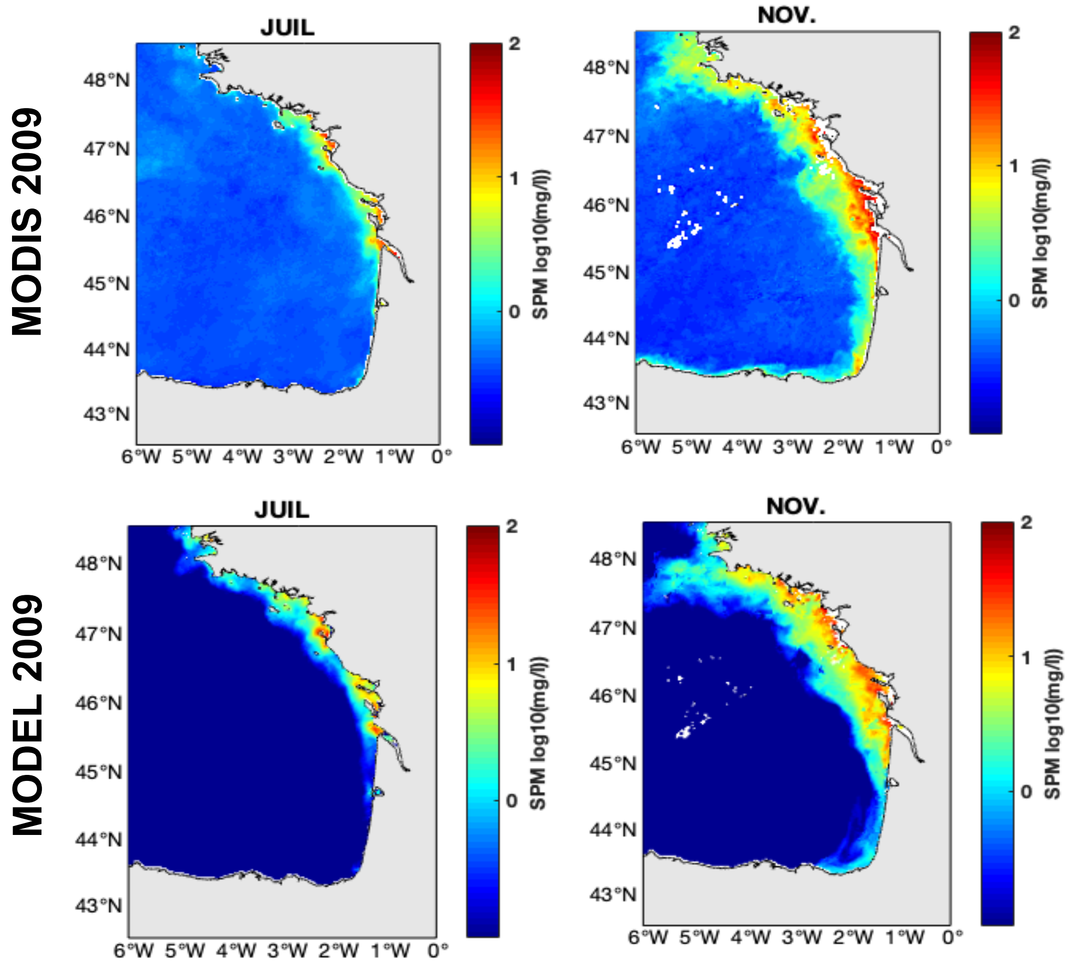
- Effect of vegetation (OBSTRUCTION module)

Some examples Bay of Biscay

CROCO-MUSTANG
dx = 2.5 km

Ongoing work
(illustrations thank to Y.Fossi Fotsi)

Satellite/Model comparison on surface concentration monthly mean



Some examples
Seine estuary

CROCO-MUSTANG
dx = 100 m