CROCO

Coastal and Regional Ocean COmmunity model

USGS within Croco

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OUTLINE

* USGS model presentation

* Recap on sediment model and features
    * Bedload formulas
    * Suspended load
    * Bed model

* Implementation of USGS within CROCO :
    * Equations
    * Code structure
    * Parameters and input files
    * Possible interfaces
        * Waves forcing
        * Bottom Boundary Layer
        * Morphodynamics

* Examples

USGS Sediment model :

* Activated with the cppkey « #define SEDIMENT »

* « legacy » model within CROCO

* Native one, from the UCLA/ROMS Communauty / USGS also called as CSTMS model (package Community Sediment Transport Modeling System), Blaas et al. (2007), Warner et al. (2008) and Shafiei et al. (2021)

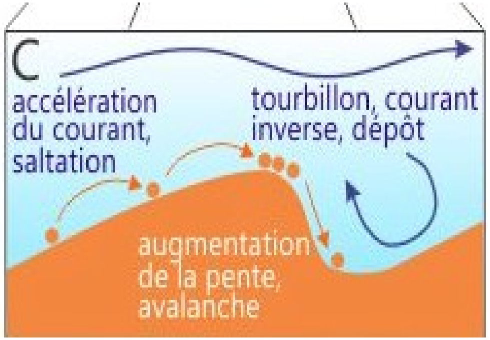
* Originally included in ROMS-AGRIF, some divergences appears with CROCO version but there are some common development

* Available in ROMS-RUTGERS and OAWST

USGS

- Recap on sediment model and features

BEDLOAD formulas



Bedload flux :

$$q_b = \Phi \sqrt{(s-1) g d_{50}^3} \rho_s$$

d_{50} : median size

ρ_s : grain density

τ_c : critical stress

$s = \rho / \rho_s$

Adding Slope effect :

$$q_b = q_b \left(\frac{0.65}{(0.65 - \tan\beta)\cos\beta} \right)$$

$\beta = \tan^{-1}(dz_b/dx)$

cppkey
#define LESSER (by default)

⇒ **Different parameterization available for the transport rate** Φ

Cppkey :
#define BEDLOAD

Bedload : Meyer-Peter Müeller (MPM) formulation

Case of rivers, continental shelves etc :

Transport rate
(class dependent) :

$$\Phi = max\left[8(\theta_s - \theta_c)^{1.5}, 0\right]$$

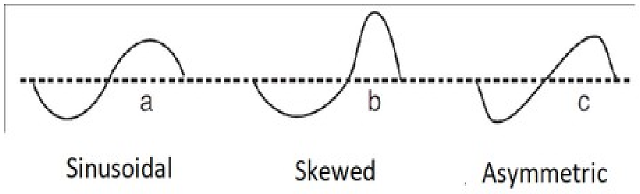
$$\theta_s = \frac{\tau_s}{(s-1)gd_{50}} \quad \text{Shield parameter}$$

θ_c : critical Shield parameter (0,047)

τ_s : skin friction

Cppkey :
#define BEDLOAD_MPM

Bedload : Vander A formulation



Case of non-linear waves : asymmetric transport, lag effect ... :

* Compute wave asymmetry effect
* Shield parameter at half cycles
* Evaluate phase lag

Transport rate
(class dependent) : crest + trough

$$\Phi = \frac{1}{T}\left[\frac{\theta_c}{\left|\theta_c\right|^{1/2}}T_c\left(\Omega_{cc}+\frac{T_c}{2T_{cu}}\Omega_{tc}\right)+\frac{\theta_t}{\left|\theta_t\right|^{1/2}}T_t\left(\Omega_{tt}+\frac{T_t}{2T_{tu}}\Omega_{ct}\right)\right],$$

$$\Omega_i = \mathcal{F}(Shield\ Cr) = \max\left(11\left(\left|\theta_i\right|-\theta_{cr}\right)^{1.2},0\right),$$

Cppkey :
#define BEDLOAD_VANDERA

Suspended transport

For each sediment class grain (non cohesive) :

Suspended sediment transport

$$\frac{\partial C}{\partial t} + \frac{\partial U_i C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K_H \frac{\partial C}{\partial x_{1,2}} + K_V \frac{\partial C}{\partial x_3} \right) + Sources / Sinks$$

Erosion rate (E0) / Settling velocity (Ws) / critical shear stress for erosion are <u>user defined</u>

Erosion formulation

$$Source = E_0 (1 - \varphi) \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \qquad \text{when } t_b > t_{ce}$$

Bottom shear stress vs critical shear stress for erosion
If positive : material are added to the water column

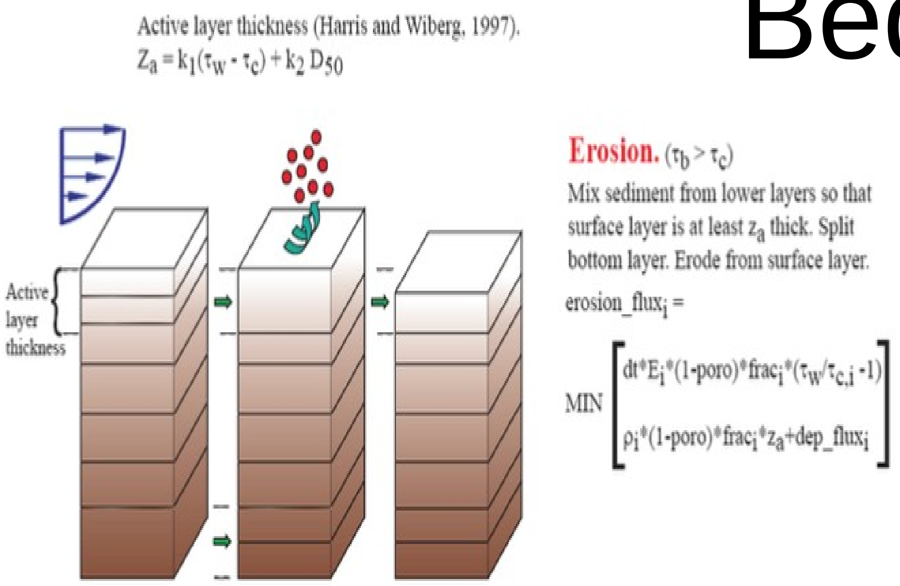
Deposition formulation

$$Sink = w_s \frac{\partial C}{\partial z}$$

Settling velocity vs tracers gradient

Cppkey : #define SUSPLOAD

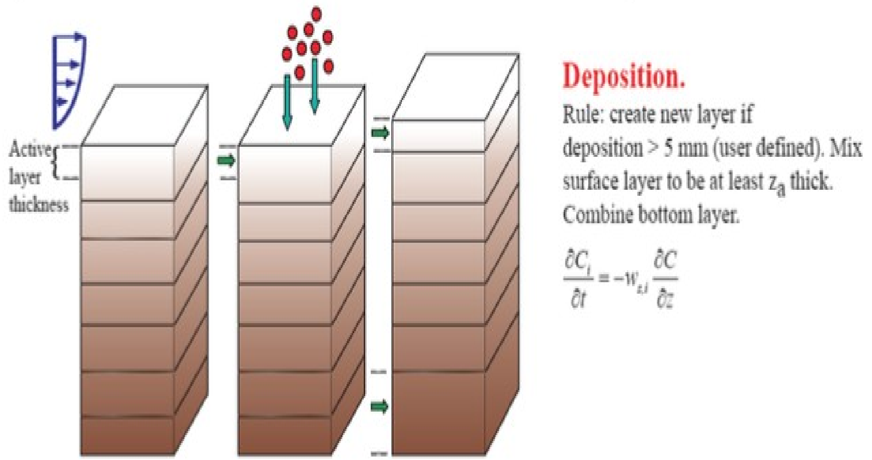
Bed model



Erosion

for $\tau_b > \tau_{ce}$

Number of layers
is fixed

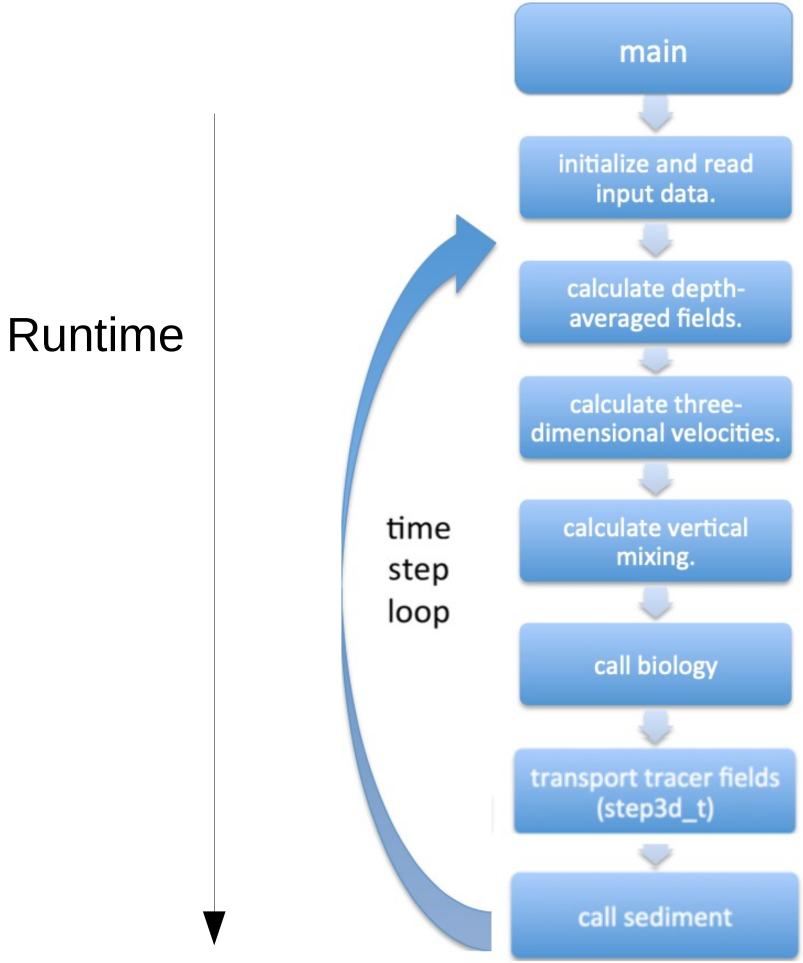


Deposition

Rule: create a new layer for deposition if top layer > 1mm

Code structure

Code structure (1)



Main program

step2d; calculates ubar, vbar, zeta

step3d_uv; calculates u, v, w

calculates water column turbulence

ifdef BIOLOGY, then calls the biology.F which will choose between the available biology modules

ifdef SEDIMENT, then calls sediment.F which calculates the suspended sediment concentration field and changes to sediment bed.

Updates tracer concentrations (salinity, temperature, sediment concentration, etc. to account for vertical and horizontal transport.

Code structure (2)

- **sediment.F** — Main program for sediment.
- **sed_bedload** — Calculates bedload sediment fluxes. Only used if "BEDLOAD" is defined.
- **sed_settling** — Calculates vertical settling of sediment. Vertical diffusion was handled outside of the sediment routines, along with diffusion of other tracers like salinity and temperature.
- **sed_fluxes** — Calculates erosion and /or deposition from the bed for each sediment class.
- **sed_bed** — Updates the sediment bed grain size distributions based on erosion, deposition, and the bed layering algorithm.
- **sed_surfaces** — Updates the properties of the sediment surface (like grain size distribution, bedform dimensions, etc.)

Model options

Sediment parameters

- Hard coded
  - Number of layers
  - Number of sediment classes

=> in param.h

```
!
# ifdef SEDIMENT
! NSAND          Number of sand classes
! NMUD           Number of mud classes
! NGRAV          Number of gravel classes (not implemented...)
! NST            Number of sediment (tracer) size classes
! NLAY           Number of layers in sediment bed
!
      integer NSAND, NMUD, NGRAV, NST, NLAY
#  ifdef DUNE
#   ifdef ANA_DUNE
      parameter (NSAND=1, NMUD=0, NGRAV=0)
      parameter (NLAY=11)
#   else
      parameter (NSAND=2, NMUD=0, NGRAV=0)
      parameter (NLAY=10)
#   endif
#  elif defined SED_TOY
#   if defined SED_TOY_RESUSP || defined SED_TOY_CONSOLID
      parameter (NSAND=2, NMUD=2, NGRAV=0)
      parameter (NLAY=41)
#   elif defined SED_TOY_FLOC
      parameter (NSAND=4, NMUD=15, NGRAV=0)
      parameter (NLAY=20)
#   elif defined SED_TOY_ROUSE
      parameter (NSAND=0, NMUD=6, NGRAV=0)
      parameter (NLAY=1)
#   endif
#  else
      parameter (NSAND=2, NMUD=0, NGRAV=0)
      parameter (NLAY=1)
#  endif
      parameter (NST=NSAND+NMUD+NGRAV)
      parameter (ntrc_sed=NST)
# else
      parameter (ntrc_sed=0)
# endif /* SEDIMENT */
!
```

Model options

Sediment CPP keys

- Main keys :
  - SEDIMENT
  - SUSPLOAD
  - BEDLOAD

=> stick with default choices

Related CPP options:

SUSPLOAD	Activate suspended load transport
BEDLOAD	Activate bedload transport
MORPHODYN	Activate morphodynamics
BEDLOAD_VANDERA	van der A formulation for bedload (van der A et al., 2013)
BEDLOAD_MPM	Meyer-Peter-Muller formulation for bedload (Meyer-Peter and Muller, 1948)
SLOPE_LESSER	Lesser formulation for avalanching (Lesser et al, 2004)
SLOPE_NEMETH	Nemeth formulation for avalanching (Nemeth et al, 2006)
BEDLOAD_UP1	Bedload flux interpolation: upwind 1rst order
BEDLOAD_UP5	Bedload flux interpolation: upwind 5th order
BEDLOAD_WENO5	Bedload flux interpolation: WENO 5th order
ANA_SEDIMENT	Set analytical sediment size, initial ripple and bed parameters
ANA_BPFLUX	Set kinematic bottom flux of sediment tracer (if different from 0)
SPONGE_SED	Gradually reduce erosion/deposition near open boundaries

Preselected options:

```
#ifdef SEDIMENT
# undef  MUSTANG
# define ANA_SEDIMENT
# define SPONGE_SED
# define Z0_BL
# define Z0_RIP
# ifdef BEDLOAD
#  ifdef BEDLOAD_VANDERA       /* default BEDLOAD scheme  */
#  elif defined BEDLOAD_MPM
#  elif defined BEDLOAD_WULIN
#  elif defined BEDLOAD_MARIEU
#  else
#   if (defined WAVE_OFFLINE || defined WKB_WWAVE ||\
        defined ANA_WWAVE    || defined OW_COUPLING)
#    define BEDLOAD_VANDERA
#   else
#    define BEDLOAD_MPM
#   endif
#  endif
```

Model options

Input file

- Dans croco.in :

```
sediments: input file
           sediment.in
sediment_history_fields: bed_thick bed_poros bed_fra(sand,silt)
                              20*F
```

- Additional file at run time : sediment.in

  Consistent with param.h :
    - Number of layers
    - Number of sediment classes

```
1  Stitle (a80)
CROCO - Sediment - Test

2  Sd(1-NST), CSED, SRHO,  WSED,  ERATE,  TAU_CE, TAU_CD, BED_FRAC(1:NLAY)
      0.125   9.9   2650.  9.4    25.0e-5  0.05    0.14    0.4  0.4
      0.050   0.0   2650.  1.6     4.0e-5  0.01    0.14    0.6  0.6

3 BTHK(1:NLAY)
       1.    10.

4 BPOR(1:NLAY)
       0.41  0.42

5 Hrip
       0.03

6 Lrip
       0.14

7 bedload_coeff
       0.

8 morph_fac
      10.

99 END of sediment input data
```

> **Sd** : Diameter of grain size class [mm].

> **CSED** : Initial concentration (spatially uniform) [kg/m3].

> **SRHO** : Density of sediment material of size class [kg/m3].

Quartz: SRHO=2650 kg/m^3

> **WSED** : Settling velocity of size class [mm/s].

Typically (Soulsby, 1997):

WSED = 10^3 $(visc\,(\sqrt{10.36^2 + 1.049 D^3} - 10.36)\,/\,D_{50}$ [mm/s]

with $D = D_{50}\,(g\,(\mathrm{SRHO}/\rho_0 - 1)\,/\,(visc^2)\,)^{0.33333}$

$D_{50} = 10^{-3} Sd$ [m]

$visc = 1.3\ 10^{-3}/\rho_0$ [m2/s]

> **ERATE** : Erosion rate of size class [kg/m2/s].

Typically:

ERATE $= 10^{-3}\ \gamma_0$ WSED SRHO $[kg/m^2/s]$

with $\gamma_0 = 10^{-3} - 10^{-5}$ (Smith & McLean, 1977)

> **TAU_CE** : Critical shear stress for sediment motion [N/m2]

(initiation of bedload for coarses, suspension for fines). Typically : $\mathrm{TAU}_C\mathrm{E} = 6.4\ 10^{-7}\ \rho_0\ \mathrm{WSED}^2$ [N/m2]

> **TAU_CD** : Critical shear stress for deposition of cohesive sediments [N/m2]

> **BED_FRAC** : Volume fraction of each size class in each bed layer (NLAY columns)

[0<BED_FRAC<1]

Possible interfacing

No Interfacing

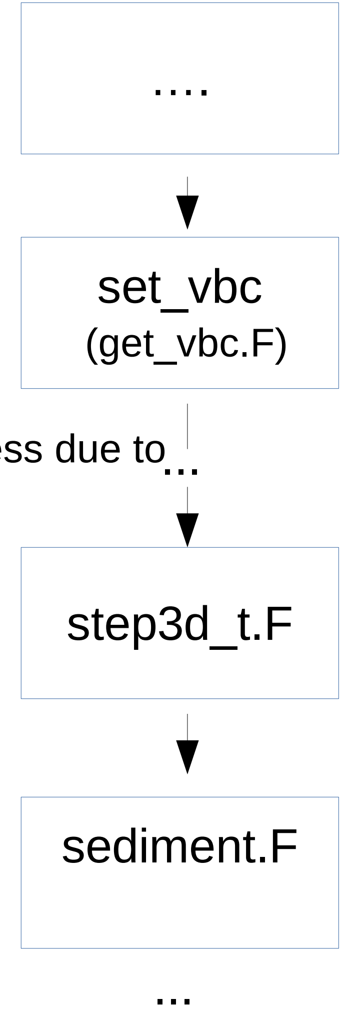
*** Hydrodynamics + Sediment routines (by default)**

Runtime

Croco.in (user defined) :
Bottom drag : rdrg/rdgr2 + Z0

Compute Bottom stress due to current : bustr

*** Sediment.in (user defined) :**
→ #ANA_SEDIMENT
* or input file .nc



vertical boundary conditions for momentum and tracers.

advection/diffusion parts of the transport term

Cppkey :
#define SEDIMENT

Waves forcing overview

Description	Analytical	Internal Wave Maker	Embedded wave model within Croco		Online data	Offline data
	Specified / constant value	Waves resolving simulation (Non boussinesq / w solve explicitely)	WKB primary waves and empirical breaking model parameters with offshore wave amplitud/period boundary conditions		Spectral wave model (WW3..)	clim/reanalysis (ERA5...)
			Initialized by croco.in	boundary forcing from other wave data		
Advantages	Cheap	better resolved at the bottom / no use of wave average equation	Cheap / No waves generation / parametrizations for wave breaking and bottom drag		Realistic	
cppkey	#ANA_WWAVE	#WAVE_MAKER #NBQ	#WKB_WWAVE #ANA_BRY_WKB	#WKB_WWAVE	#OW_COUPLING	#WAVE_OFFLINE
routine	analytical.F	wave_maker*.h	wkb_wwave.F		get_wwave.F	
				get_bry_wkb.F		
Parameters	Hs,T,DD	Hs,T,DD...	Hs, T, DD + breaking parameters			
User def. file	Analytical.F	wave_maker*.h	Croco.in (wkb_wwave/wkb_roller)			

⇒ Estimate wave associated variables usually pass to wave current interaction (#MRL_WCI) (based on wave average equation, compute additional terms , stokes drift) and Bottom Boundary layer (#BBL) routines

Bottom boundary layer

<u>Goal</u> :

* Variability of gradients in velocity and suspended-sediment concentrations near the bottom
* Take account of the change of rugosity due to sediment in bottom stress computation
* Parameterize the effect of surface waves on bottom stresses and apparent roughness

⇒ **BBL formulation :**

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

- account for current stress at the bottom
- account for wave stress

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

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

- sediment dependant Z0
- account of vertical elevation z which will vary in time and spatially

⇒ Bottom stress then is updated for sediment transport :

* For Bedload :

$$\theta_s = \frac{\tau_s}{(s-1)gd_{50}}$$

* For erosion/suspension :

$$Source = E_0(1-\varphi)\frac{\tau_b - \tau_{ce}}{\tau_{ce}}$$

Interfacing

*** Hydrodynamics + BBL + waves + sediment routines**
(#define BBL)

...

set_vbc
(get_vbc.F)

*** Waves input :**
#define OW_COUPLING (WW3.nc...)
#define WKB_WWAVE
#define ANA_WWAVE

Hs,Tp,DD, (/ breaking param/ Ub...)

bbl.F

Bedform roughness estimate at the bottom (mean surface properties) :

Sdensity/Ssize/ taucb /settling velocity

Combined Wave/Current Bottom stress : bostr / w(max) + Ripple (Height/Length) + Zbapparent + Ub

step3d_t.F

*** Sediment inputs :**
* by an input file (.nc)

* sediment.in :
→ #define ANA_SEDIMENT

sediment.F

*** Update**
3D bed properties (fraction / mass / thickness ...)
2D bottom properties (Sdensity...)

Model options

BBL

Related CPP options:

BBL	Activate bottom boundary layer parametrization
ANA_WWAVE	Set analytical (constant) wave forcing (hs,Tp,Dir).
ANA_BSEDIM	Set analytical bed parameters (if SEDIMENT is undefined)
Z0_BL	Compute bedload roughness for ripple predictor and sediment purposes
Z0_RIP	Determine bedform roughness ripple height and ripple length for sandy bed
Z0_BIO	Determine (biogenic) bedform roughness ripple height and ripple length for silty beds

Preselected options:

```
#ifdef BBL
# ifdef OW_COUPLING
# elif defined WAVE_OFFLINE
# elif defined WKB_WWAVE
# else
#  define ANA_WWAVE
# endif
# ifdef SEDIMENT
#  undef  ANA_BSEDIM
# else
#  define ANA_BSEDIM
# endif
# ifdef SEDIMENT
#  define Z0_BL
# else
#  undef  Z0_BL
# endif
# ifdef Z0_BL
#  define Z0_RIP
# endif
# undef  Z0_BIO
#endif
```

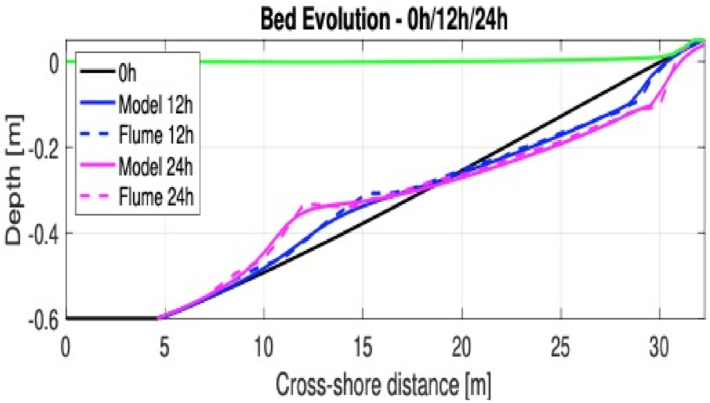
Morphodynamics

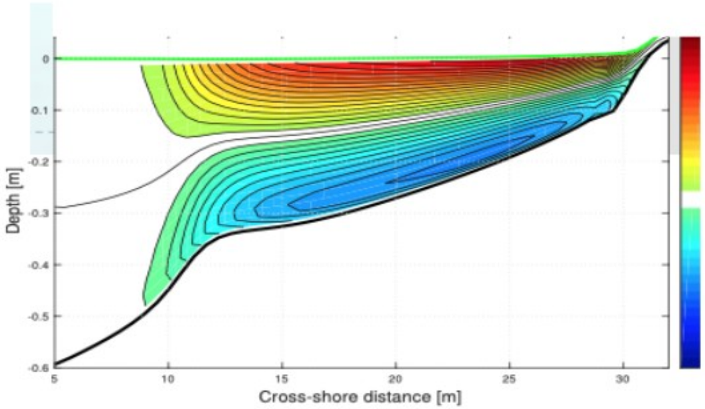
Ex Sandbar test case :

Exner equation : divergence of sediment fluxes

$$\frac{\partial z_b}{\partial t} = -\frac{f_{mor}}{1-p}\left(\frac{\partial q_b}{\partial x} - w_s\frac{\partial C}{\partial z} + E\right).$$

i.e. difference between erosion and deposition
+ bedload fluxe



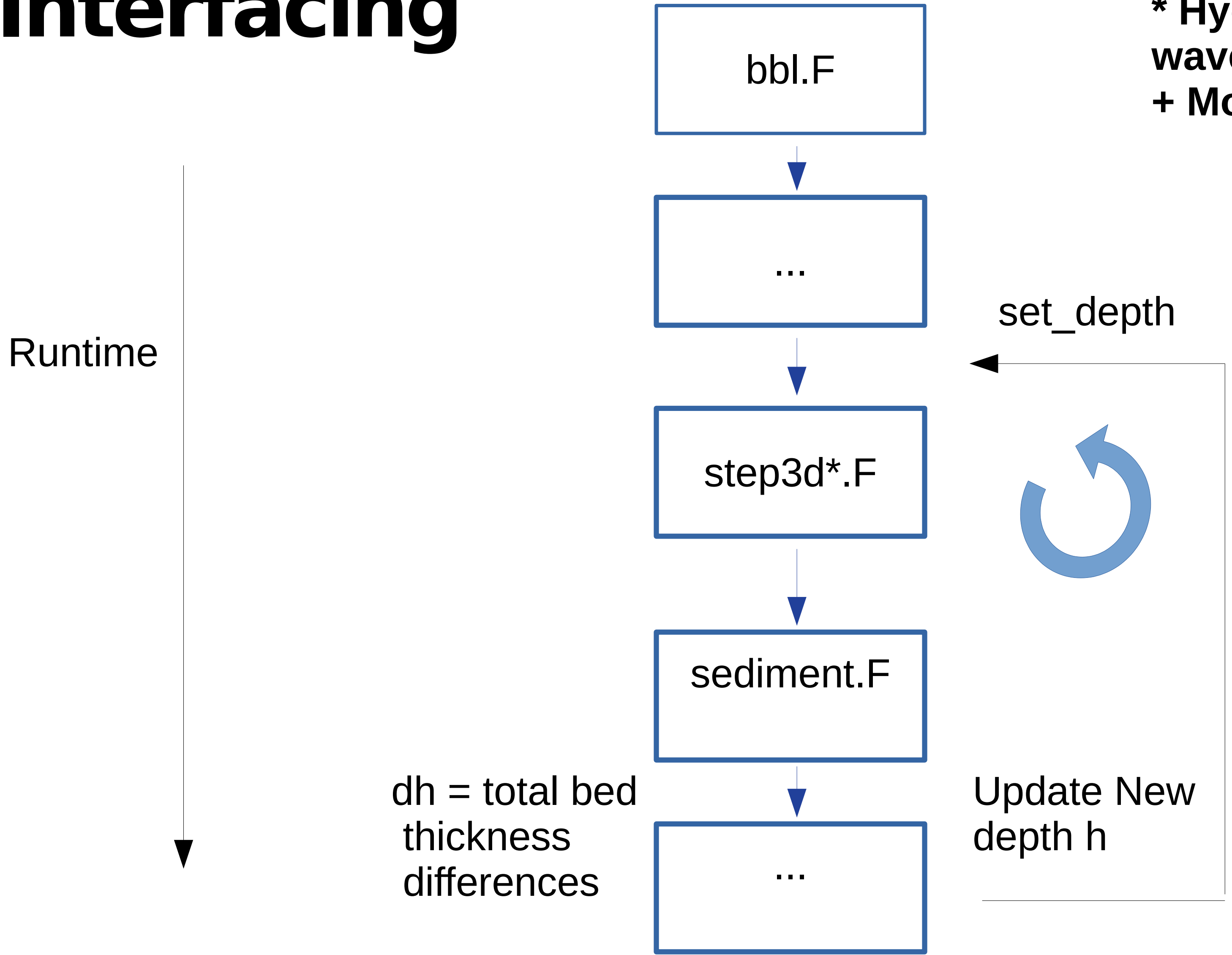


* modification of vertical velocity
* acceleration of bed response
* speed-up equilibration

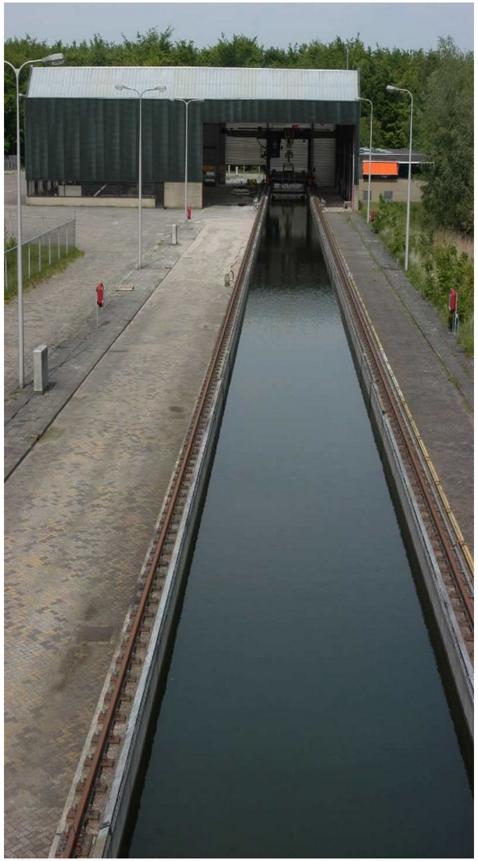
* change morphodynamics, change the dynamics, change the circulation , then move the bed

Interfacing

*** Hydrodynamics + BBL + waves + Sediment routines + Morphodynamics**



Sandbar



Goal :

To predict onshore and offshore sandbar migrations under storm and post-storm conditions

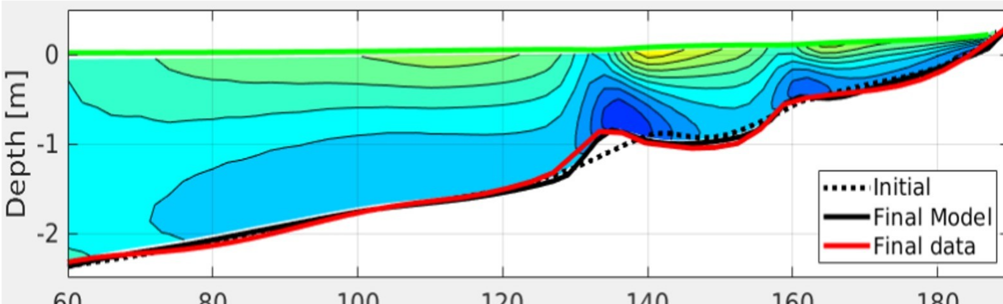
To Fit well with sandbar experiment data from European Large Installation Plan (LIP) :

* LIP-1B (characterizing erosion of sandbar) **SANDBAR_OFFSHORE**
* LIP-1C (accretion) **SANDBAR_ONSHORE**

Different Wave Forcing methods :

* Wave statistics from WKB wave model that will initialize a Bottom Boundary Layer and Use of wave current interactions

* Use of Wave maker for wave-resolving simulations in Non hydrostatic mode (NBQ) (need high resolution at the bottom)



t_0

Initialize beach profile with linear slope

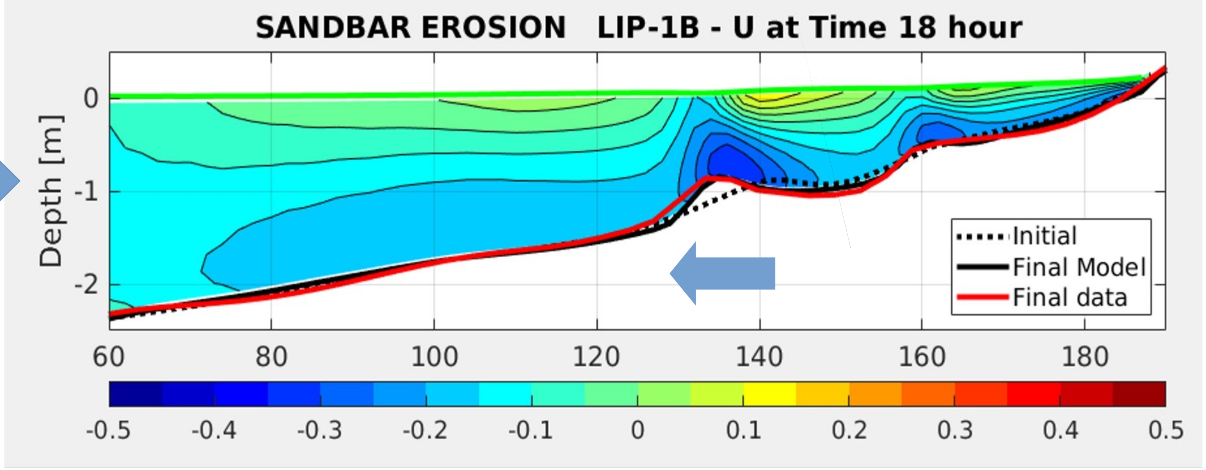
Dean number $De=H_s/T_pW_s$
(Erosion vs Accretion)
W_s=25mm/s

t_1

High energy waves :

H_s=0,45m

T_p = 5s



De =3,6

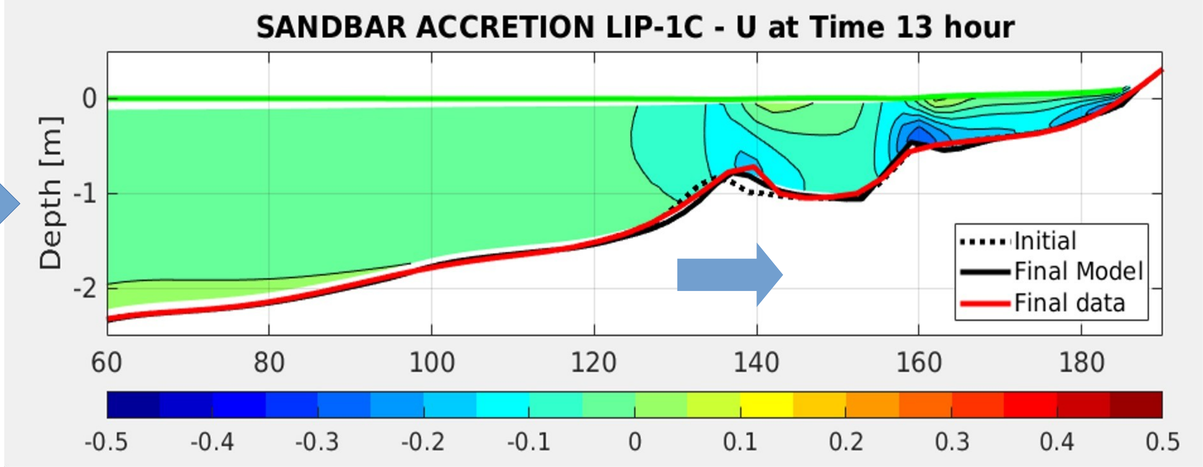
⇒ **Erosion**

$t_2=t_1$+18h

Low energy waves :

H_s =0,18m

T_p=8s

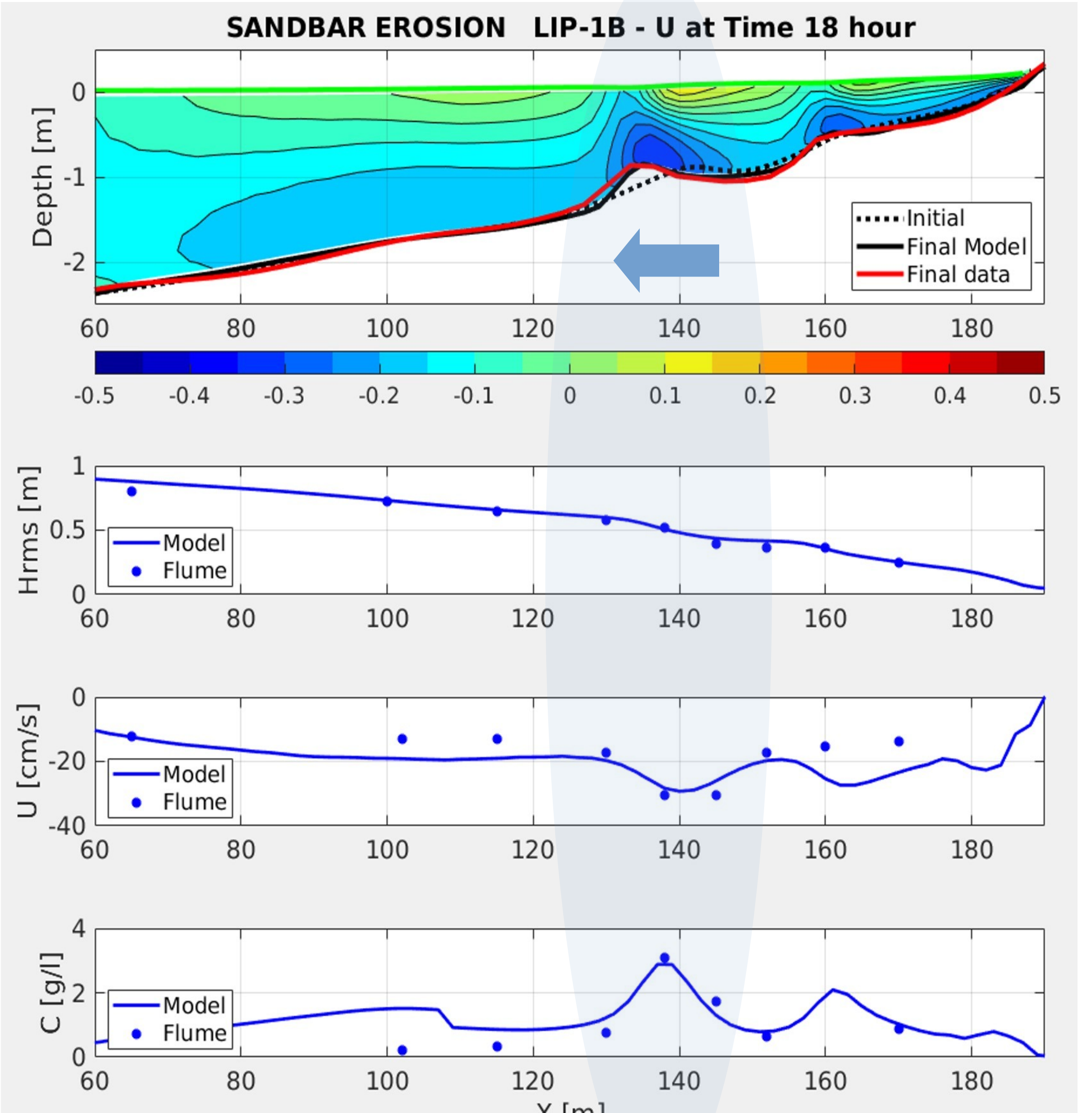


De=0,9

⇒ **Accretion**

t_2+13h

Validation with LIP-1B flume experiment



* Transport increase onshore to offshore

* Hrms : root-mean-square wave height (fit well with flume data)

* Undertow

* Bottom Concentration is correlated with undertow
Resuspended material greater

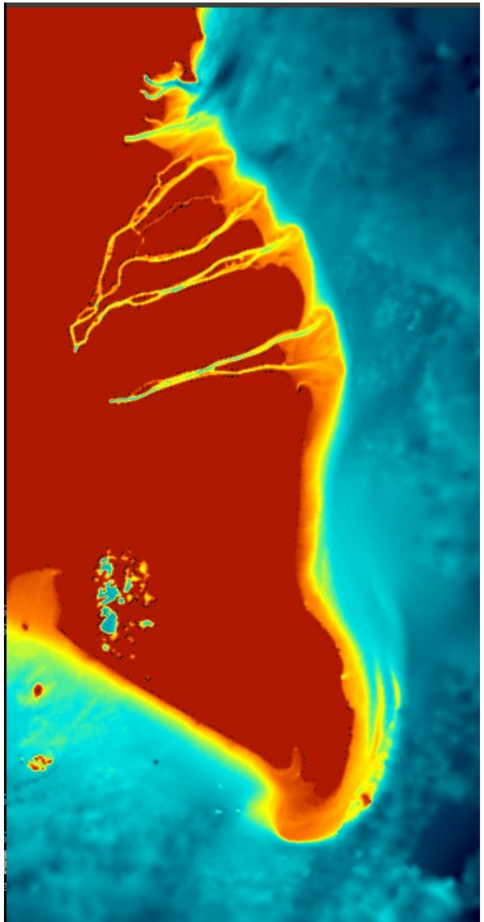
Examples 1

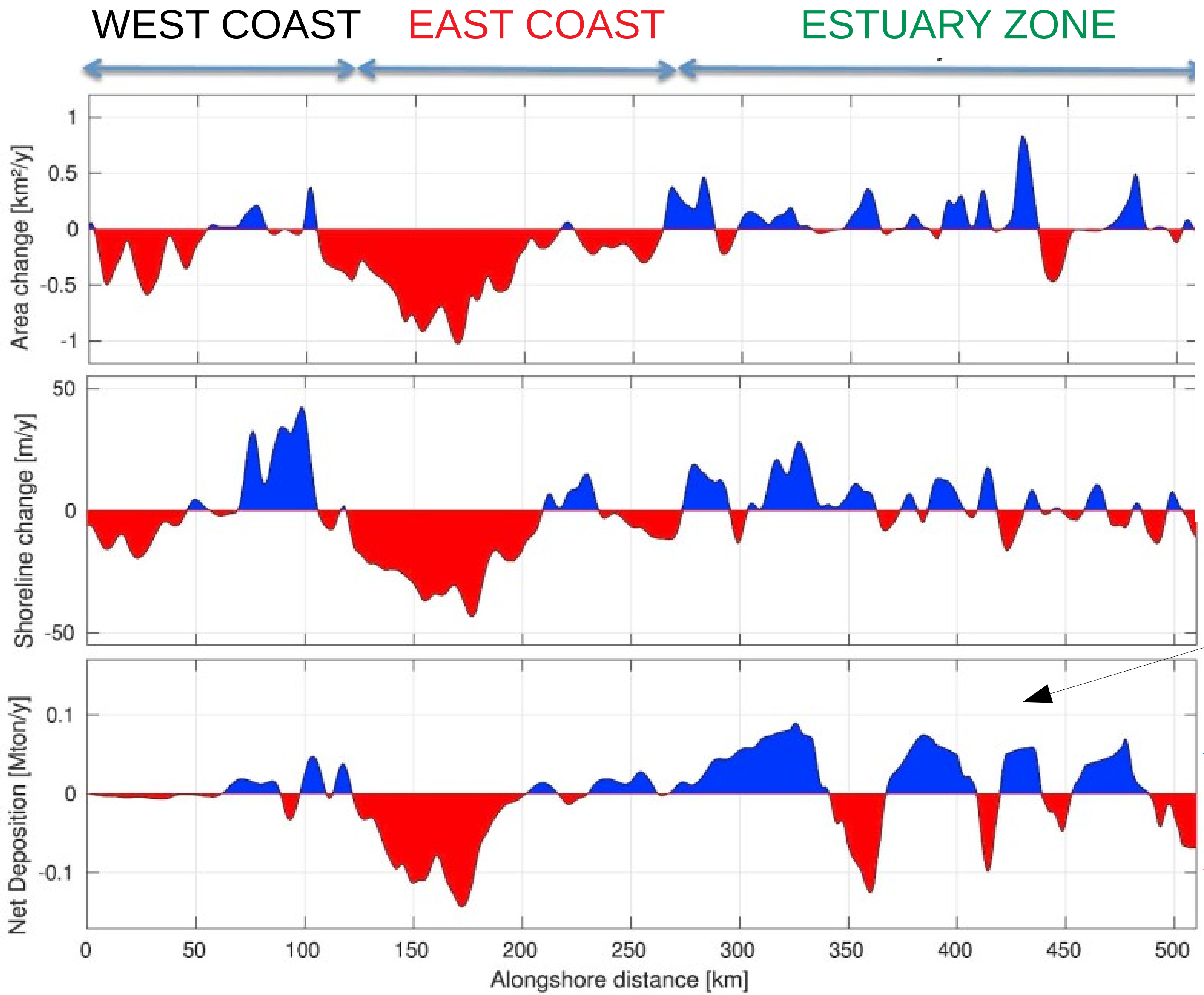
*** Study of accretion / erosion processes due to interaction between Mekong river / tides / waves**

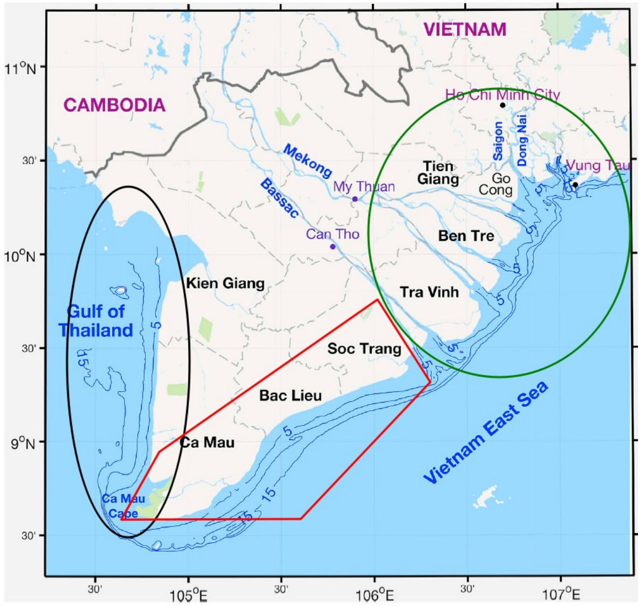
→ Configuration Croco **LMDCZ** (Updated version):

Resolution	550m	
Grid rectangular rotated grid Lx/Ly Lz	376/729 (374/727 calcul) 10	207/400 km 42,7m
bathy	SIWWR data + GEBCO	
RUNOFF	Clim from obs (2017-2019)	1m
Tide	TPXO9 v5 (1/30°)	
Oforc	Reanalysis GLORYS (1/12)	0,25° 1d
Aforc	ERA5	0.25° 1h
Wave	ERA5	0.5° 1h
Sediment (no cohesive behavior)	Sand) d50 200um Mud) d50 20um	Ws 20 mm/s Ws 0,03mm/s

2 classes of sediment







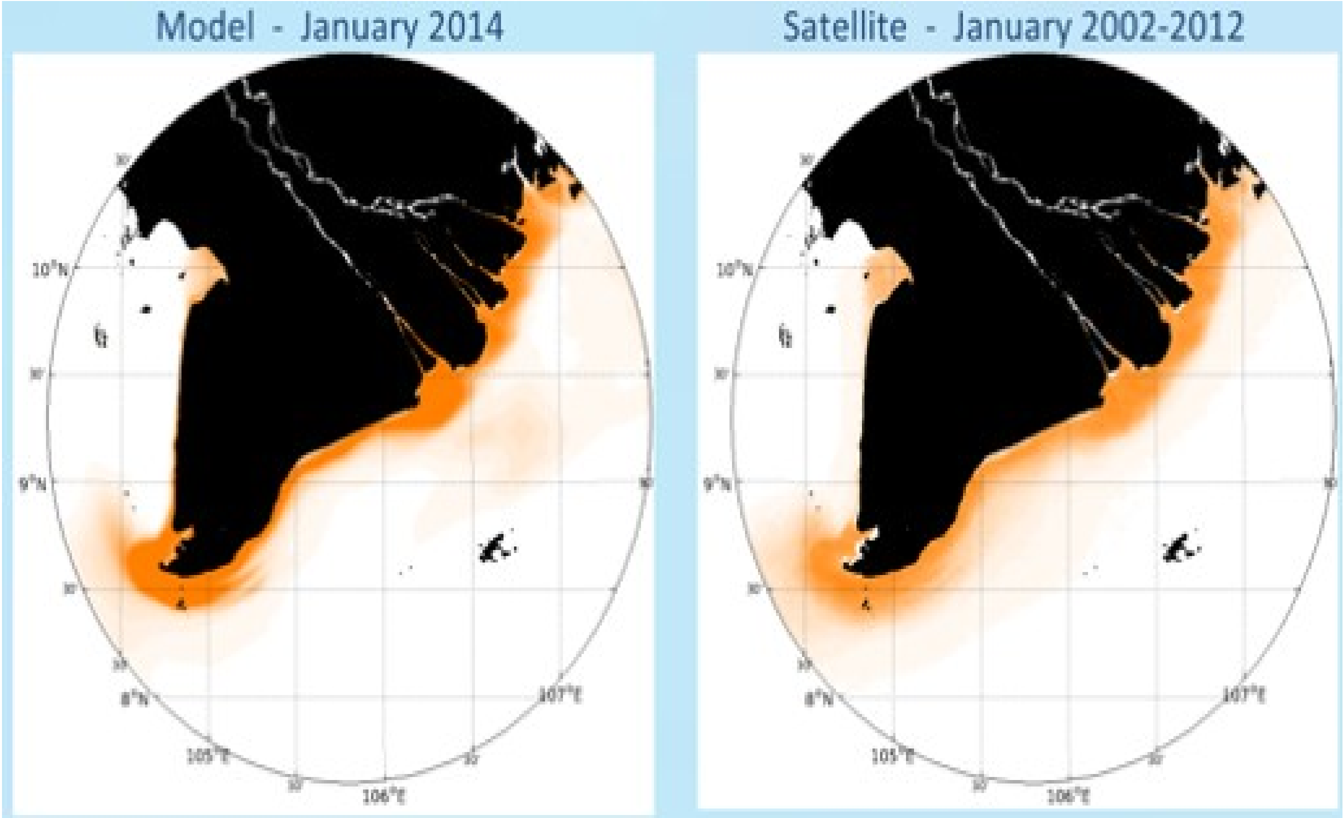
Model net deposition along the whole Mekong delta coastline

Accretion

Erosion

Validation :

Product of satellite MERIS (surface particulate matter)



Gratiot et al., 2017, Ha et al., 2018, Marchesiello et al., 2019