CROCO

Coastal and Regional Ocean COmmunity model

Sediment modeling

Implementation and use within CROCO

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

Outline

- Ocean dynamics and sediment
  - Wave averaged equations
  - Bottom boundary layer

- Models and features

- Implementation in CROCO :
  - Equations
  - Code structure
  - Model Options

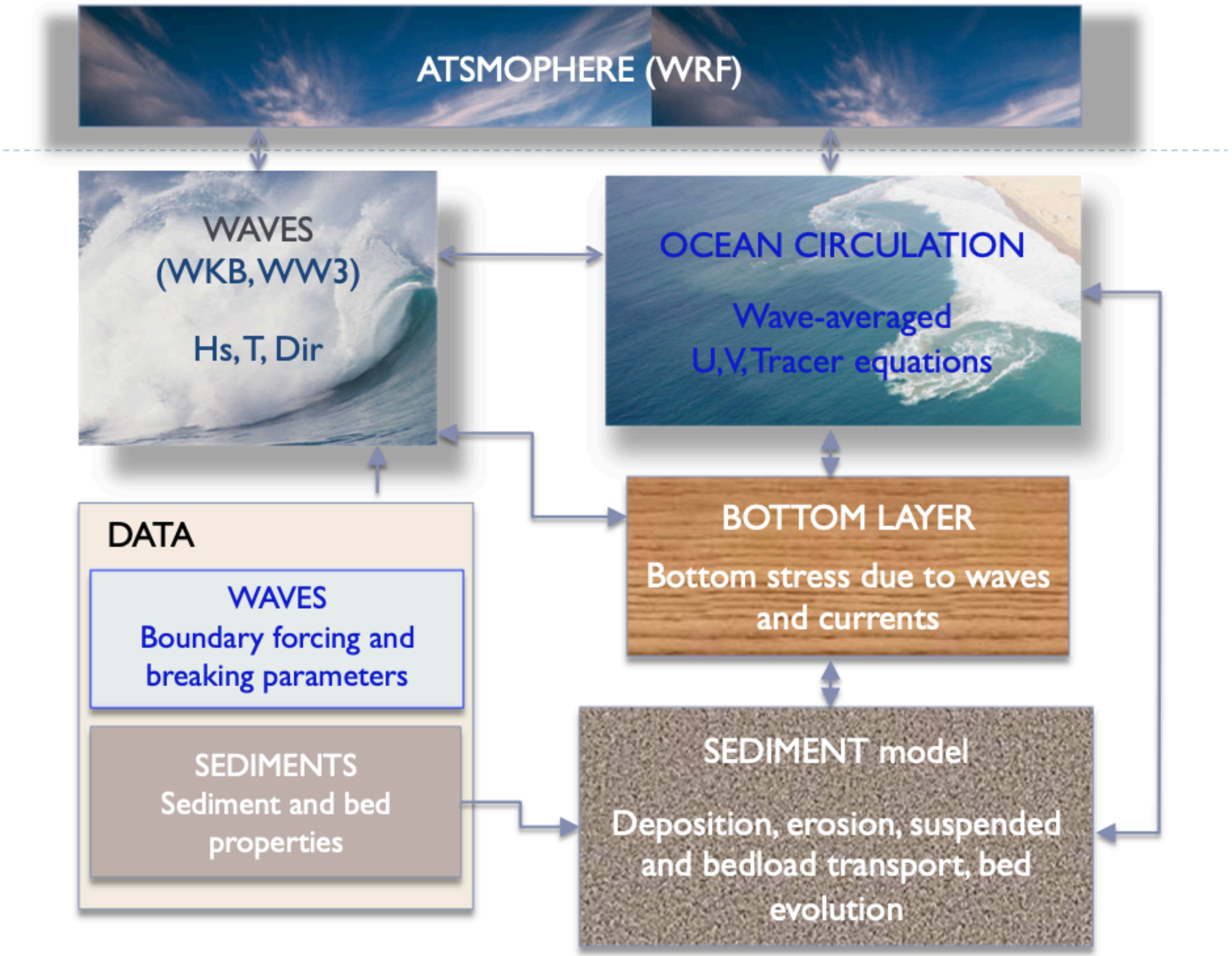
- Options, parameters and input files

- Examples

Ocean dynamics and sediment

Dynamics and sediment

Overview



ATSMOPHERE (WRF)

WAVES
(WKB, WW3)

Hs, T, Dir

OCEAN CIRCULATION

Wave-averaged
U,V, Tracer equations

BOTTOM LAYER

Bottom stress due to waves and currents

SEDIMENT model

Deposition, erosion, suspended and bedload transport, bed evolution

DATA

WAVES
Boundary forcing and breaking parameters

SEDIMENTS
Sediment and bed properties

Ocean dynamics and sediment

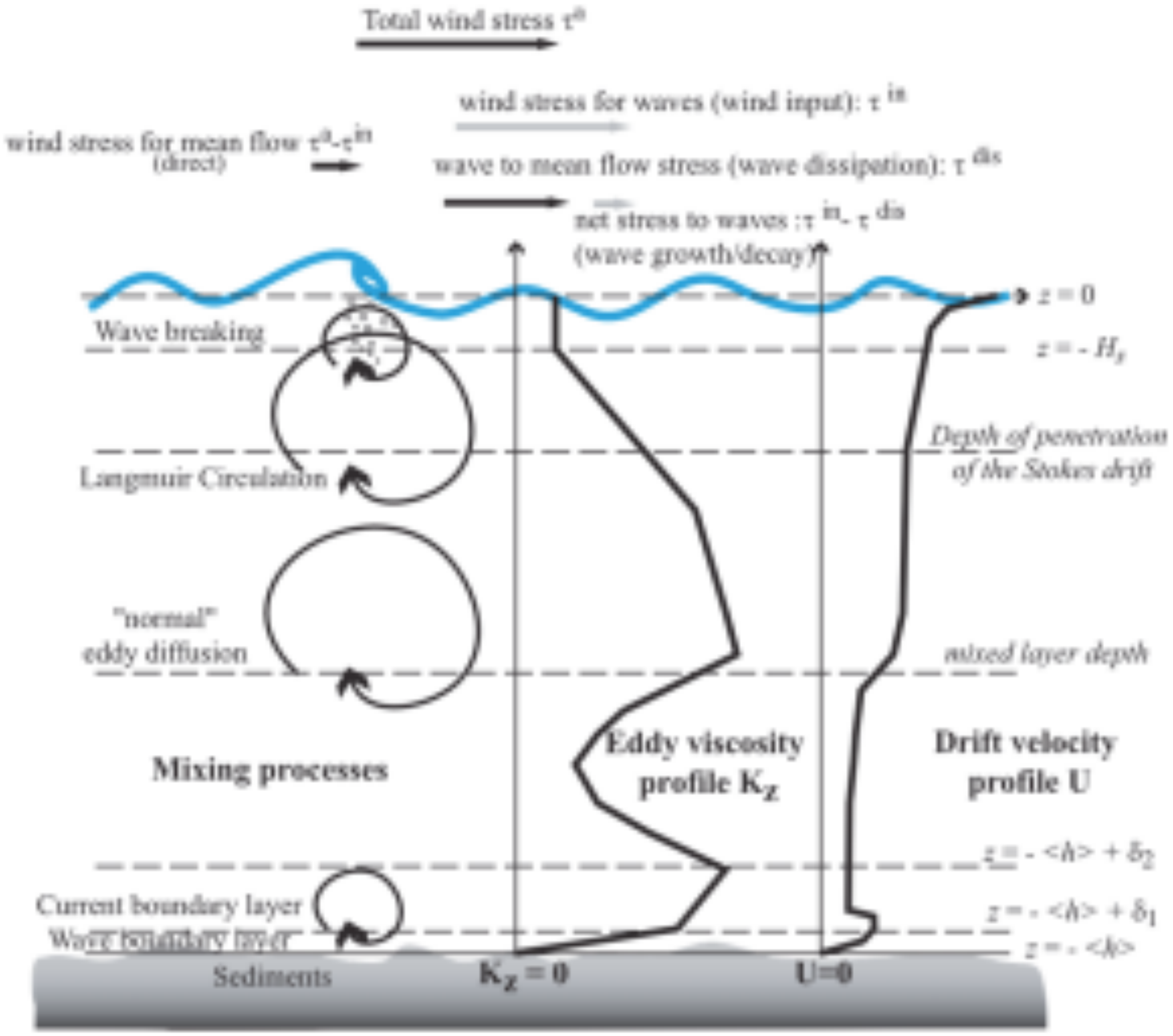
Waves averaged equations

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u} + w\frac{\partial \mathbf{u}}{\partial z} + f\hat{\mathbf{z}} \times \mathbf{u} - \nabla\phi + \mathbf{F} = \nabla\kappa + \mathbf{J} + F^w$$

$$\frac{\partial \phi}{\partial z} + \frac{g\rho}{\rho_0} = -\frac{\partial \kappa}{\partial z} + K$$

$$\nabla\mathbf{u} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial c}{\partial t} + (\mathbf{u}.\nabla)c + w\frac{\partial c}{\partial z} - \mathcal{C}\} = (\mathbf{u}^{\mathbf{st}}.\nabla)c - w^{st}\frac{\partial c}{\partial z} + \frac{\partial}{\partial z}\mathcal{E}[\frac{\partial c}{\partial z}]$$



Ocean dynamics and sediment

Bottom boundary layer

Bottom stress matters:
=> erosion and resuspension 4_0
=> bedload transport

Sediment :
=> change rugosity

Classical formulations :

$$\tau_{bx} = \left(\gamma_1 + \gamma_2\sqrt{u^2+v^2}\right)\ u$$
$$\tau_{by} = \left(\gamma_1 + \gamma_2\sqrt{u^2+v^2}\right)\ v$$

$$\tau_{bx} = \frac{\kappa^2}{\ln^2\left(z/z_0\right)}\sqrt{u^2+v^2}u$$
$$\tau_{by} = \frac{\kappa^2}{\ln^2\left(z/z_0\right)}\sqrt{u^2+v^2}v$$

=> BBL formulation :

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

$$\tau_c = \frac{\kappa^2}{\ln^2\left(z/z_0\right)}|u|^2$$
$$\tau_w = 0.5\rho f_w u_b^2$$

- account for current stress at the bottom
- account for wave shear stress
- Sediment dependent z0

Models and features

Models and features

Sediment modeling : models

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 (just released)

Models and features

Sedimentmodeling : models and processes

- both model focus on non-cohesive sediment

- Same (main) processes for both

- Developments underway for cohesive processes

- In this presentation : USGS only

- but :
    - MUSTANG documented
    - Test cases with both models (Guillaume presentation)

Models and features

Sediment modeling : main processes in CROCO

- Transport in the water column
- Erosion / deposition
- Bedload transport
- Bed evolution (sand, mud, mixed)
- Morphological evolution

IMPLEMENTATION

EQUATIONS

Implementation

Transport

For each class of sediment :

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

C : sediment concentration

$\vec{\mathbf{v}}$: Lagrangian velocity

- multiple sediment classes :

grain size, density, settling velocity, erosion rate, bed porosity, and critical shear stress for erosion

- advection-diffusion (like T & S, bio etc)
- monotonic scheme (eventually)
- zero-flux boundary condition (diffusion)
- standard boundary conditions

Implementation

Deposition

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

=> settling velocity w_s

- sink term
- constant velocity (input parameter)
- class (size) dependent

Implementation

Erosion : non-cohesive case

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

- source term
- erosion flux (sea-floor only)
- class (size) dependent

$$E = E_0(1-p)\,\phi\left(\frac{\tau_s}{\tau_c} - 1\right) \text{ for } \tau_s > \tau_c$$

E_0 : erosion rate

p : porosity

ϕ : sediment fraction

τ_s : shear stress

τ_c : critical stress

Implementation

Erosion : mixed or cohesive case

τ_c : critical stress

E_0 : erosion rate

p : porosity

ϕ : sediment fraction

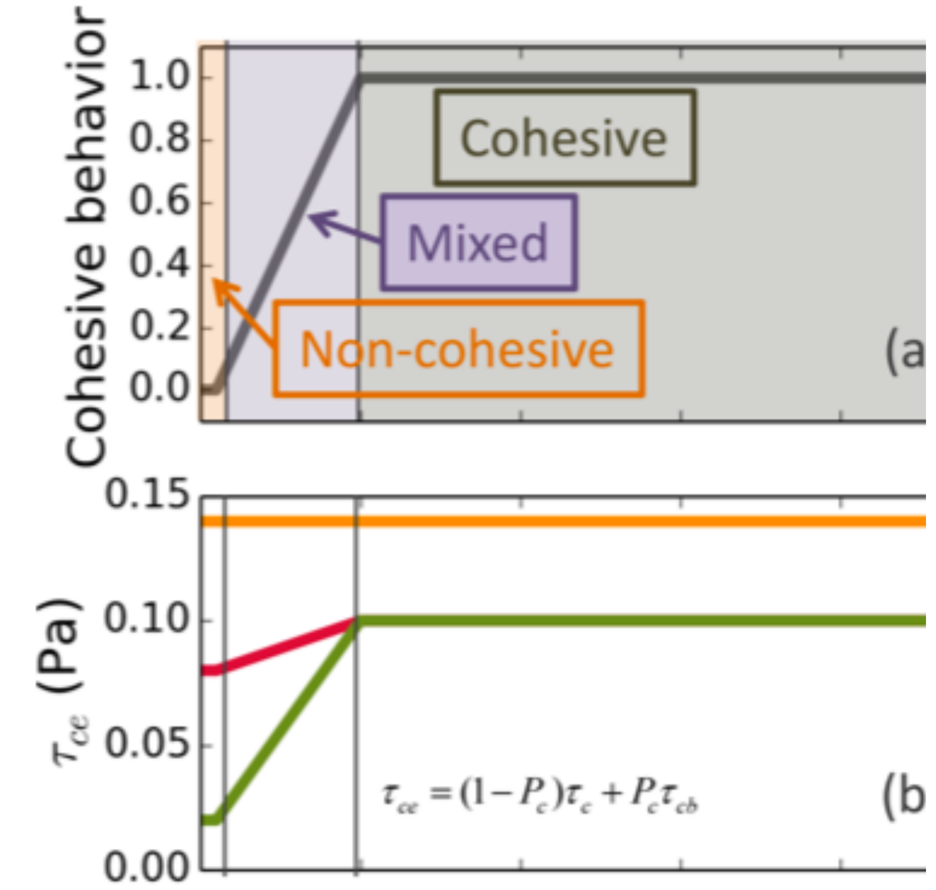
τ_s : shear stress

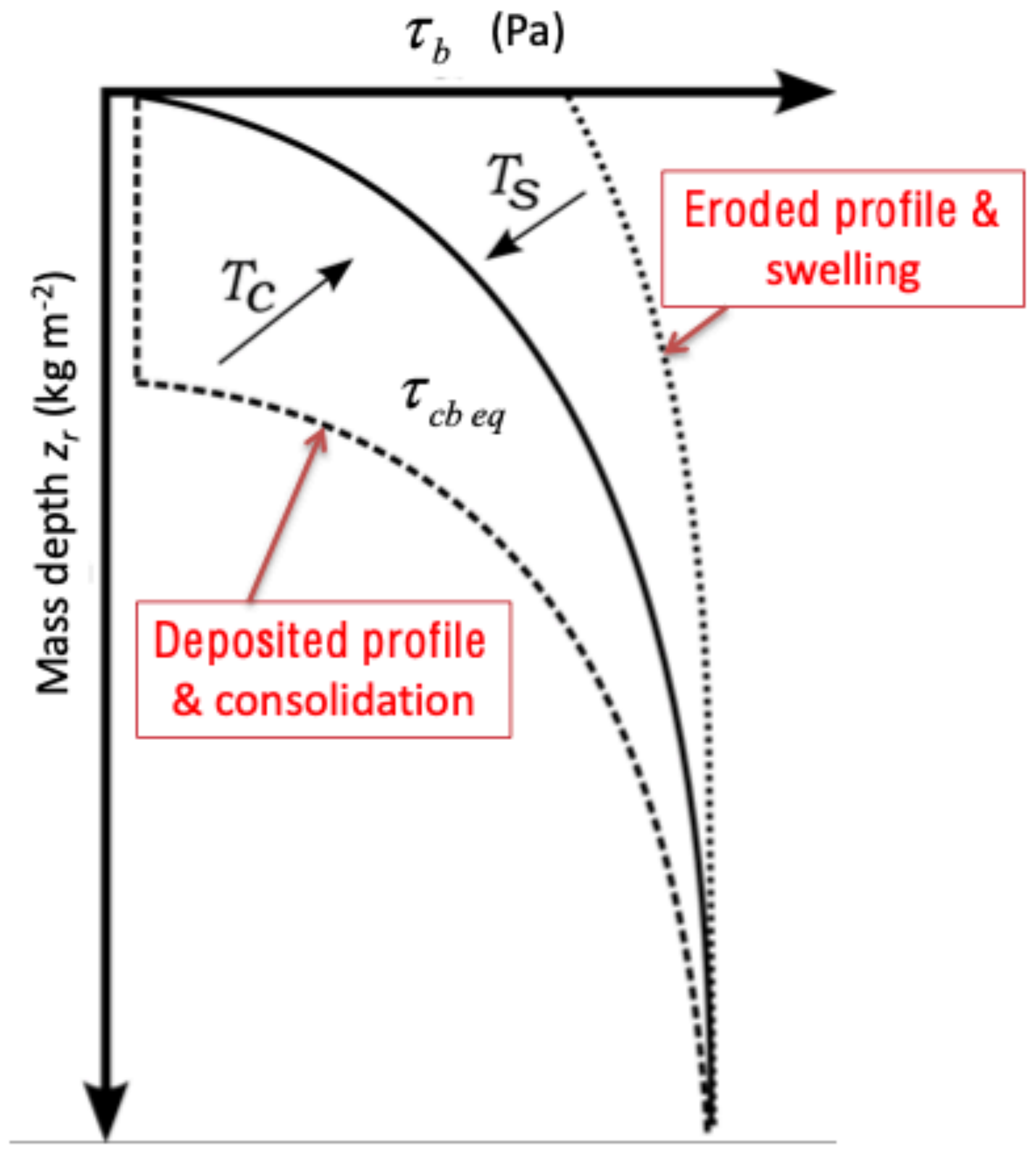
$$\underbrace{\frac{\partial C}{\partial t}}_{RATE} = -\underbrace{\vec{\nabla}.\vec{v}C}_{ADVECTION} + \underbrace{\mathcal{D}_C}_{MIXING} - \underbrace{\frac{\partial w_s C}{\partial z}}_{SETTLING} + \boxed{\underbrace{\frac{E}{\delta z_b}\Big|_{z=z_b}}_{EROSION}}$$

$$E = E_0(1-p)\,\phi\left(\frac{\tau_s}{\tau_c}-1\right) \text{ for } \tau_s > \tau_c$$

Time dependent critical stress τ_c :

- sediment classes => cohesive or not
- critical layer stress :
- erosion capacity depends on critical stress:
  - global property of the layer, not of the sediment classes
  - increases with depth
  - equilibrium profile updated at each time step
- effective instantaneous stress: damping to this equilibrium profile



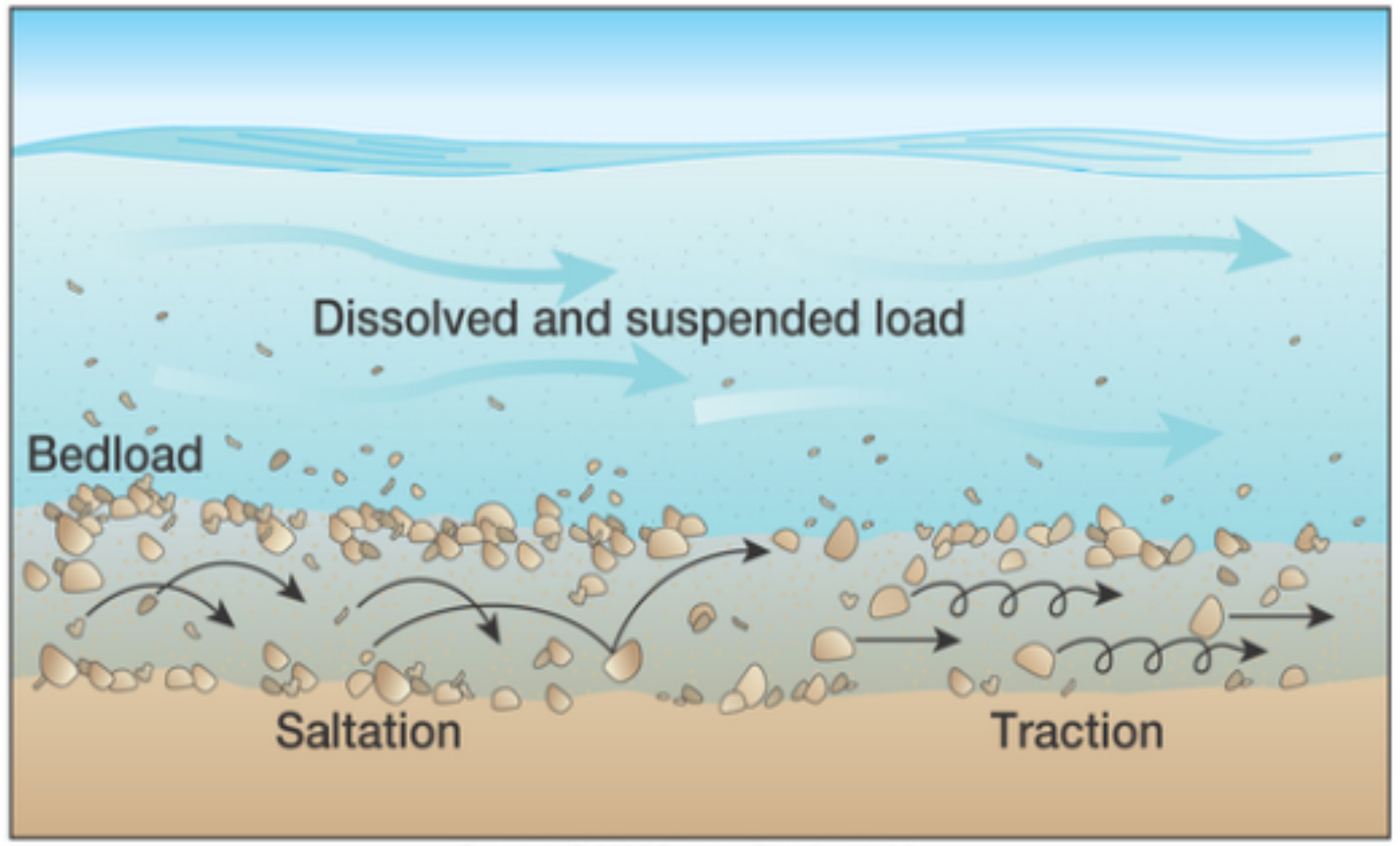


$$\tau_{\mathrm{cb\,eq}} = a\exp\left[\frac{\ln(z_p)-\mathrm{offset}}{\mathrm{slope}}\right]$$

Mixed case : $\tau_{\mathrm{ce}} = \max\left[P_c\tau_{\mathrm{cb}} + (1-P_c)\,\tau_c,\ \tau_c\right]$

Implementation

Bedload



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- not resolved explicitly
- bi-dimensional
- different parametrisations available (Φ : transport rate)

=> bedload flux

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

d_{50} : median size

ρ_s : grain density

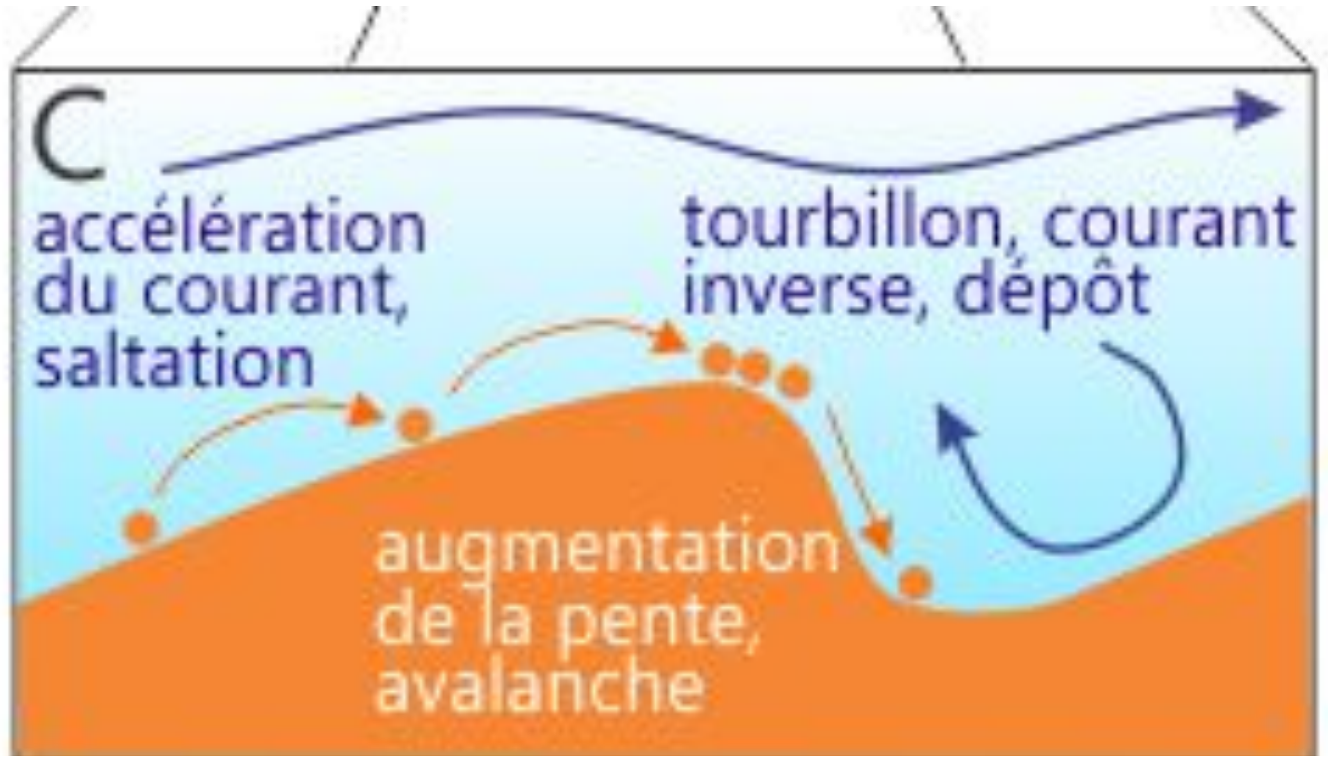
τ_c : critical stress

$s = \rho/\rho_s$

=> slope effect

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

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



Implementation

Bedload : Meyer-Peter Müeller formulation

Case of rivers, continental shelves etc

Transport rate :

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

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

$$\tau_s = \sqrt{\tau_{sx}^2 + \tau_{sy}^2}$$

Φ : transport rate (class dependent)

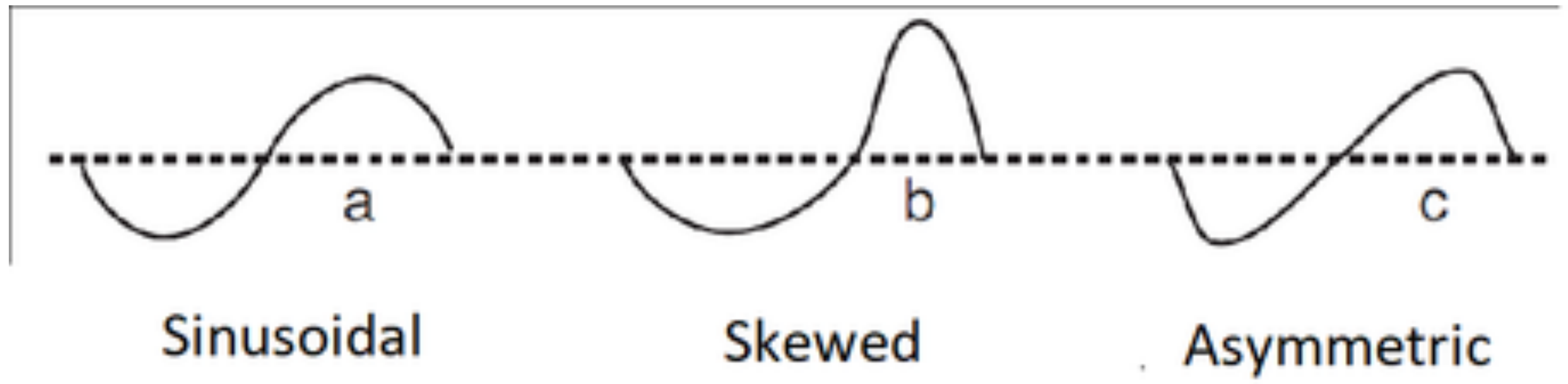
θ_s : Shield parameter

θ_s : critical Shield parameter

τ_s : skin friction

Implementation

Bedload : Van der A formulation



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

- compute asymmetry
- Shield parameter at Ralph cycle)
- Evaluate phase lag

=> Transport rate : crest + through

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

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

Implementation

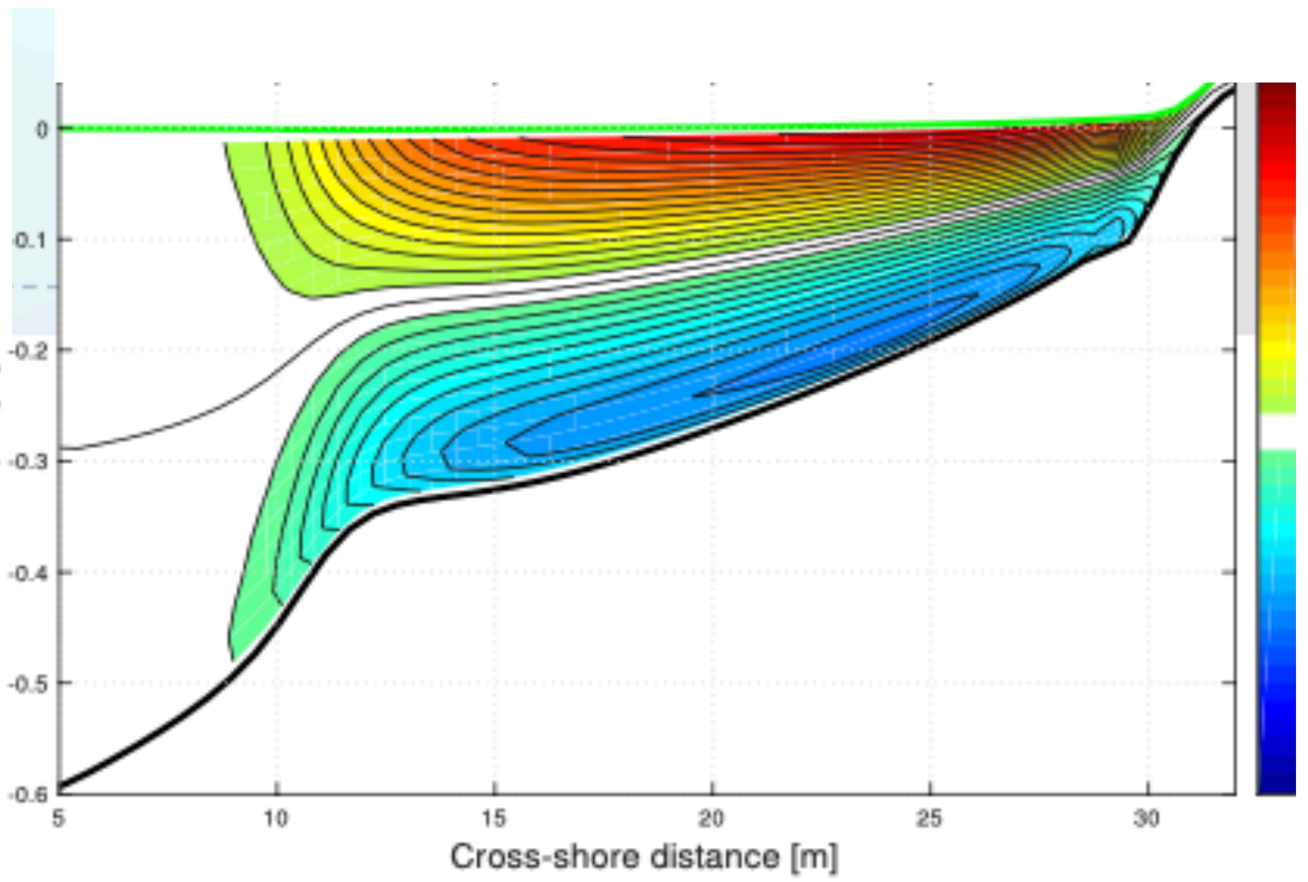
Morphodynamics

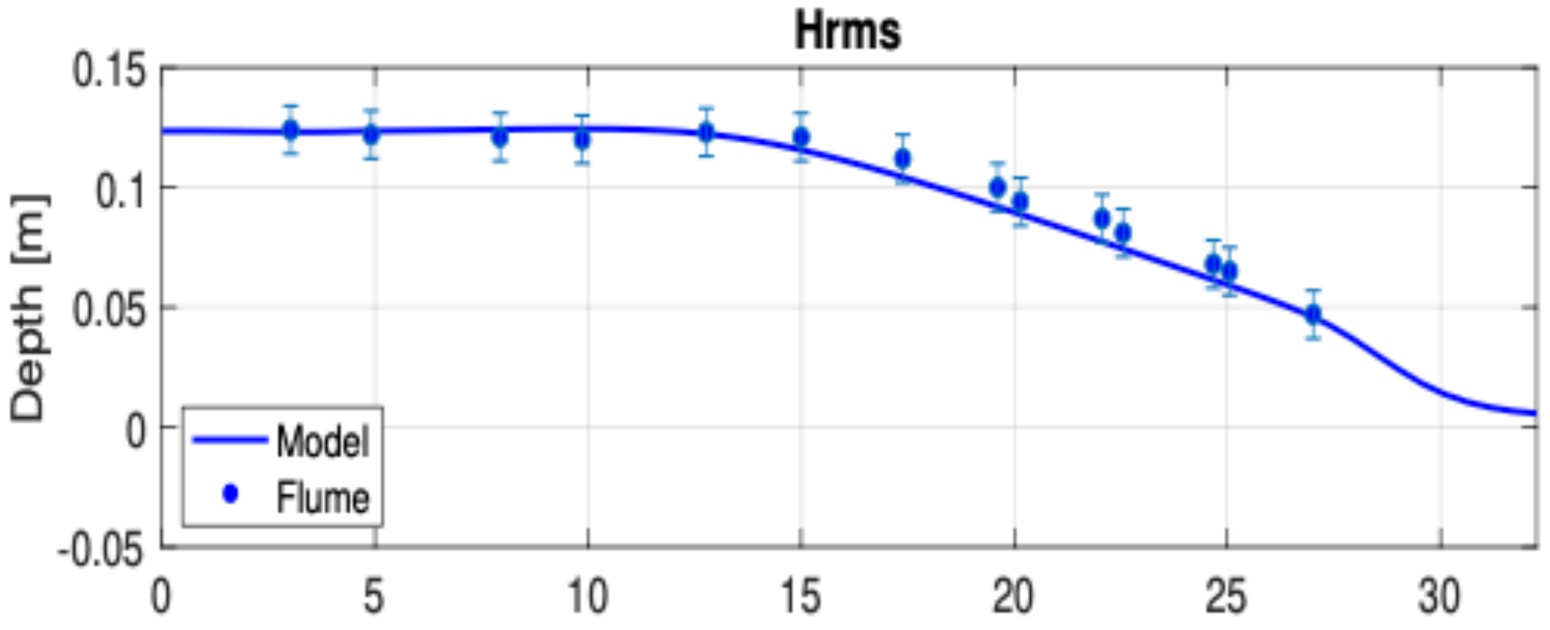
Exner equation : divergence of sediment fluxes

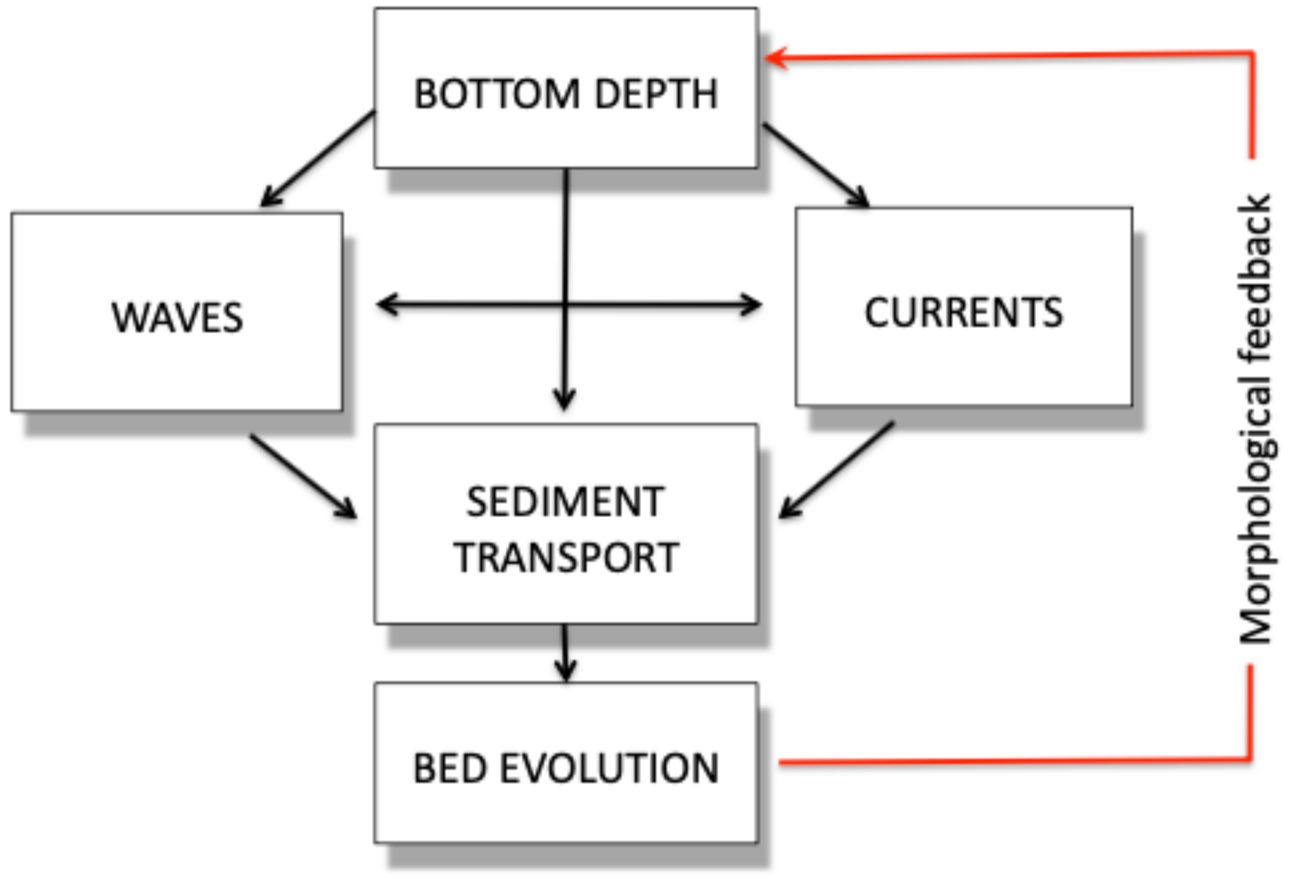
i.e. difference between erosion and deposition
+ bedload fluxe

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

- modification of vertical velocity
- speed-up equilibration







BOTTOM DEPTH

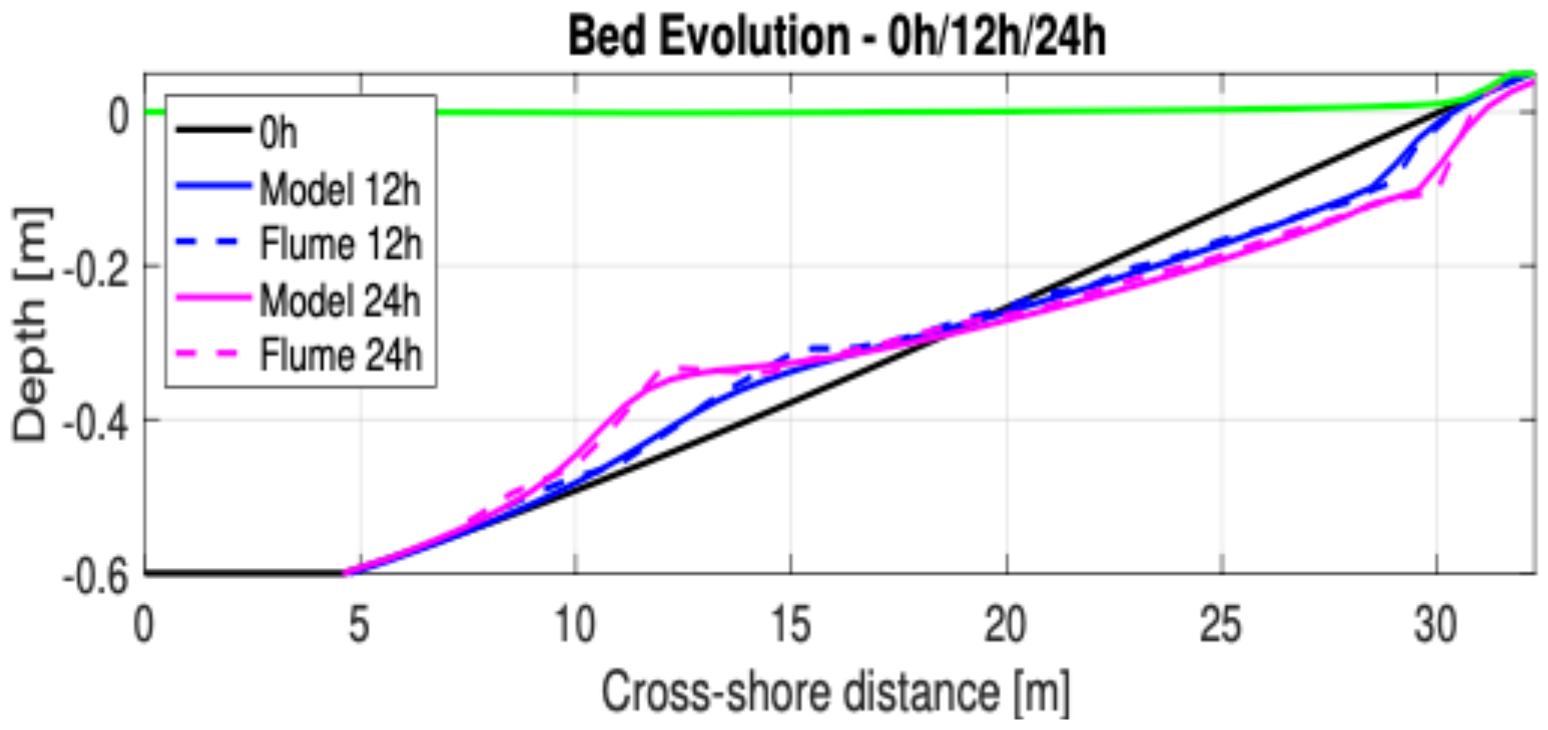
WAVES

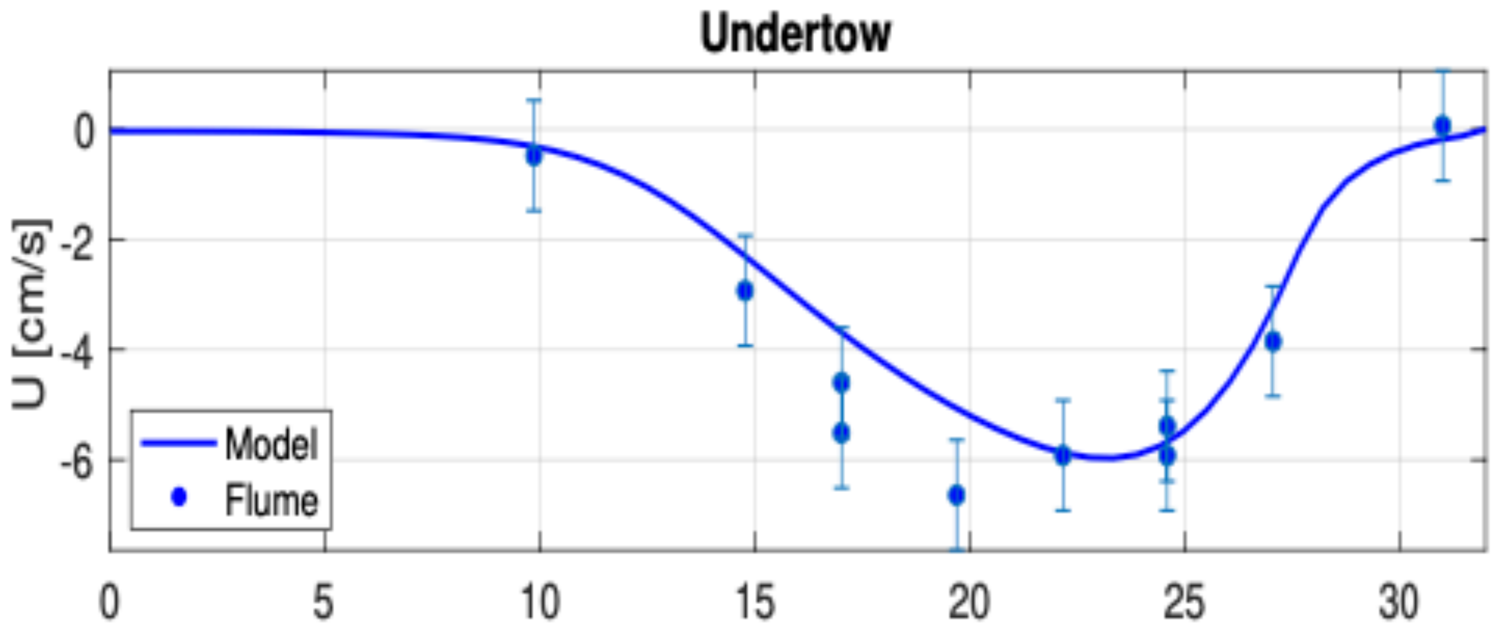
CURRENTS

SEDIMENT TRANSPORT

BED EVOLUTION

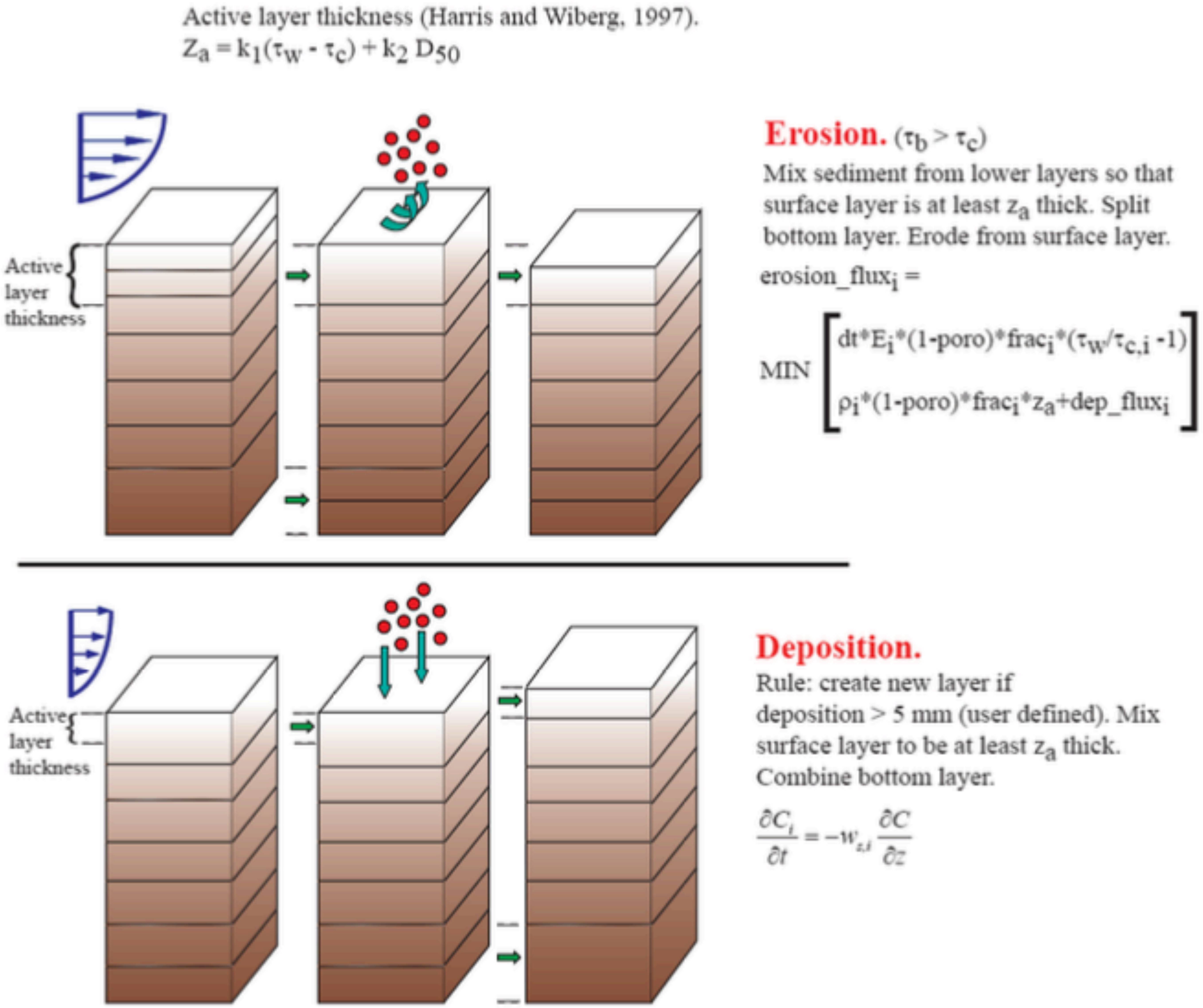
Morphological feedback





Implementation

Bed model


Active layer thickness (Harris and Wiberg, 1997).

$Z_a = k_1(\tau_w - \tau_c) + k_2 D_{50}$

Erosion. ($\tau_b > \tau_c$)

Mix sediment from lower layers so that surface layer is at least z_a thick. Split bottom layer. Erode from surface layer.

erosion_flux$_i$ =

$$\mathrm{MIN}\begin{bmatrix} dt*E_i*(1\text{-}poro)*frac_i*(\tau_w/\tau_{c,i} - 1) \\ \rho_i*(1\text{-}poro)*frac_i*z_a + dep\_flux_i \end{bmatrix}$$

Deposition.

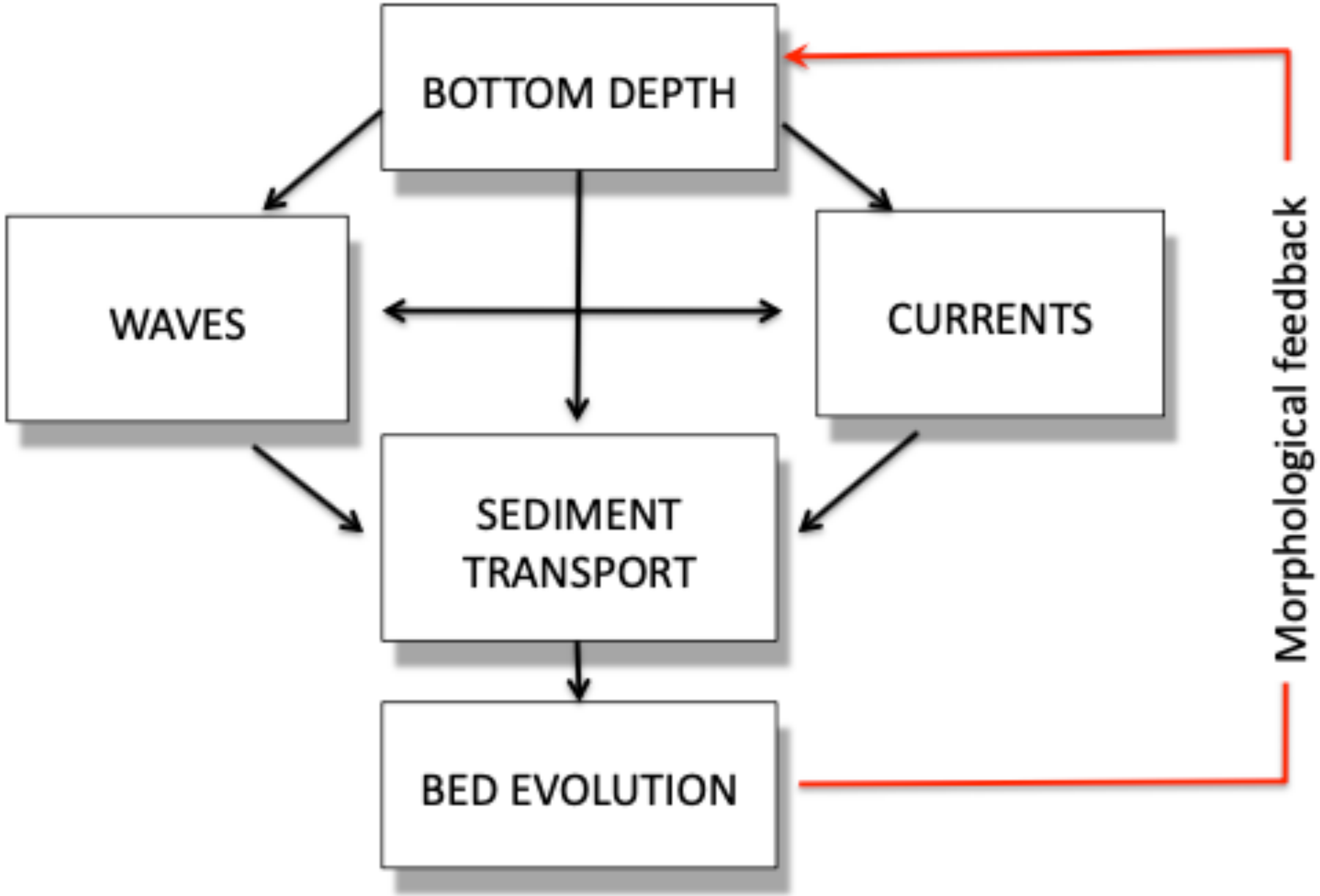
Rule: create new layer if deposition > 5 mm (user defined). Mix surface layer to be at least z_a thick. Combine bottom layer.

$$\frac{\partial C_i}{\partial t} = -w_{s,i}\frac{\partial C}{\partial z}$$

IMPLEMENTATION

CODE STRUCTURE

Code structure (1)


BOTTOM DEPTH

WAVES

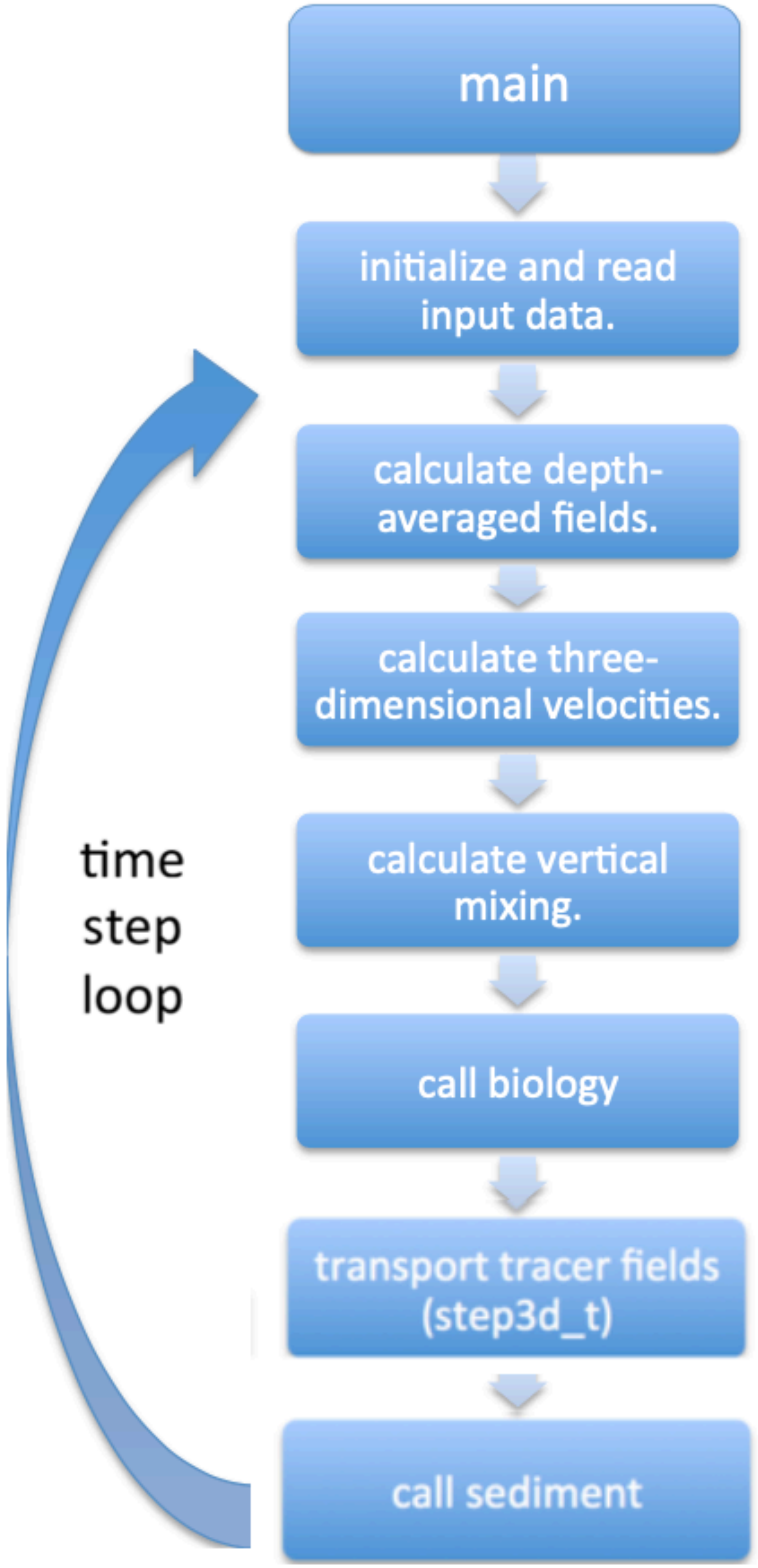
CURRENTS

SEDIMENT TRANSPORT

BED EVOLUTION

Morphological feedback

Code structure (2)



Main program

step2d; calculates ubar, vbar, zeta

step3d_uv; calculates u, v, w

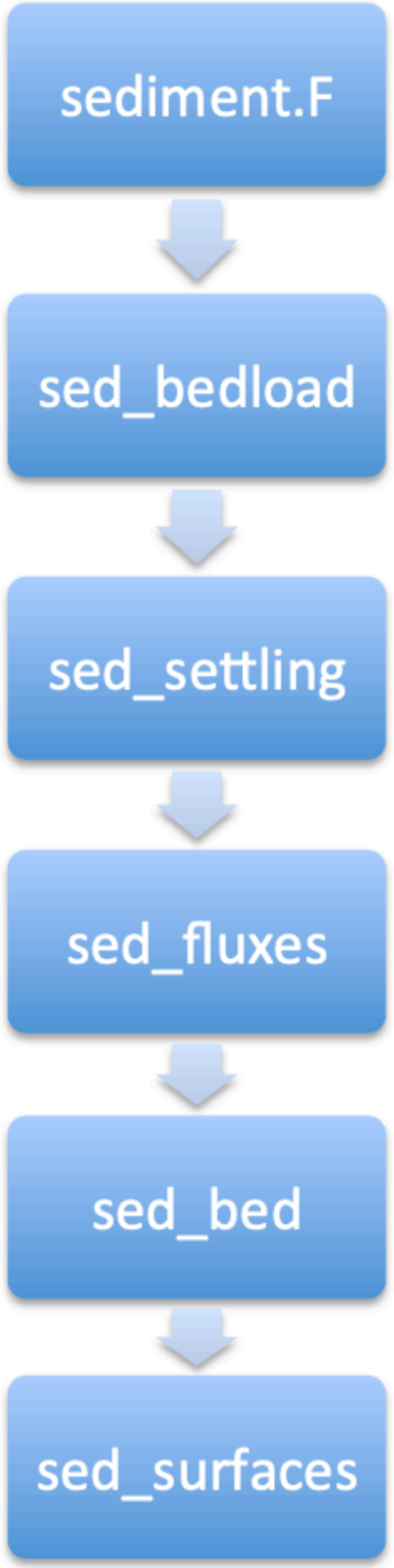
calculates water column turbulence

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.

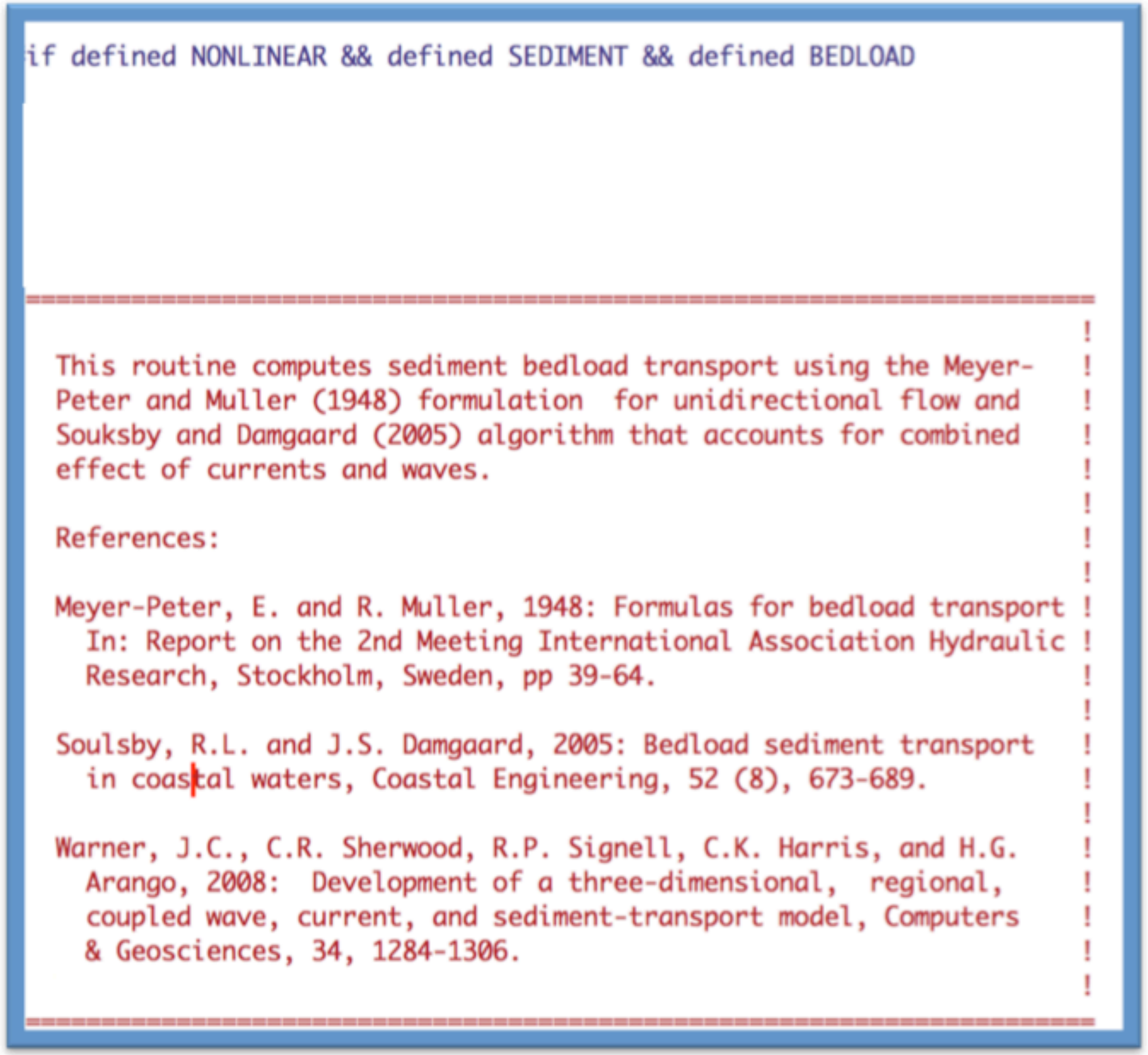
Updates tracer concentrations (salinity, temperature, sediment concentration, etc. to account for vertical and horizontal transport.

Code structure (3)



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.)

Code structure (4)

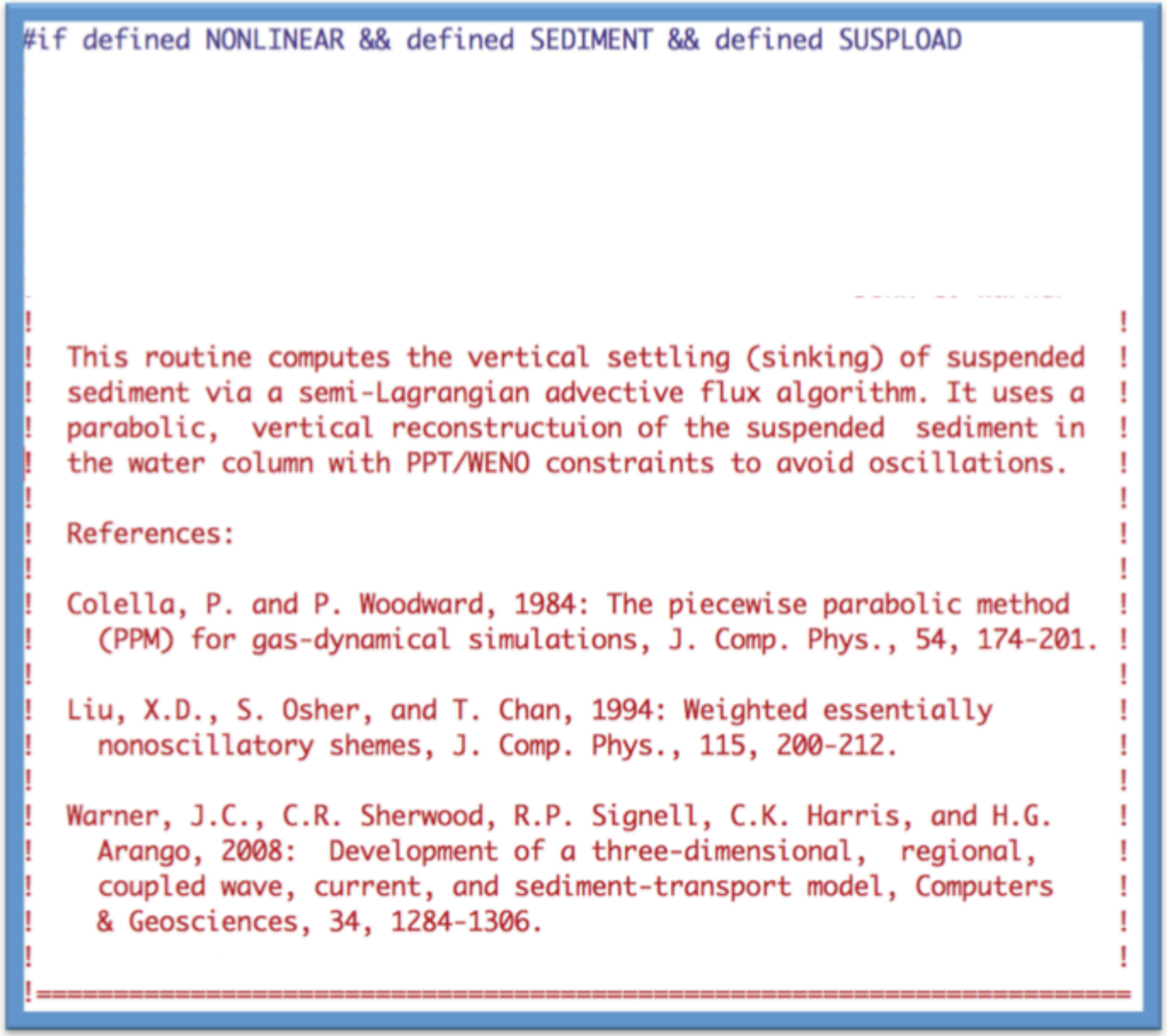


```
if defined NONLINEAR && defined SEDIMENT && defined BEDLOAD





=======================================================================
                                                                      !
  This routine computes sediment bedload transport using the Meyer-   !
  Peter and Muller (1948) formulation  for unidirectional flow and    !
  Souksby and Damgaard (2005) algorithm that accounts for combined    !
  effect of currents and waves.                                       !
                                                                      !
  References:                                                         !
                                                                      !
  Meyer-Peter, E. and R. Muller, 1948: Formulas for bedload transport !
    In: Report on the 2nd Meeting International Association Hydraulic !
    Research, Stockholm, Sweden, pp 39-64.                            !
                                                                      !
  Soulsby, R.L. and J.S. Damgaard, 2005: Bedload sediment transport   !
    in coastal waters, Coastal Engineering, 52 (8), 673-689.          !
                                                                      !
  Warner, J.C., C.R. Sherwood, R.P. Signell, C.K. Harris, and H.G.    !
    Arango, 2008:  Development of a three-dimensional,  regional,     !
    coupled wave, current, and sediment-transport model, Computers    !
    & Geosciences, 34, 1284-1306.                                     !
                                                                      !
=======================================================================
```

sed_bedload

1. Calculate correct bed stresses.
2. Calculate bedload transport rate using one of two relationships.
3. Accounts for bed slope.
4. Calculate bedload flux convergence and divergence that lead to erosion and deposition.
5. Limit erosion to amount of sediment available, and deposition to not shoaling.
6. Updates sediment bed properties.

Code structure (5)

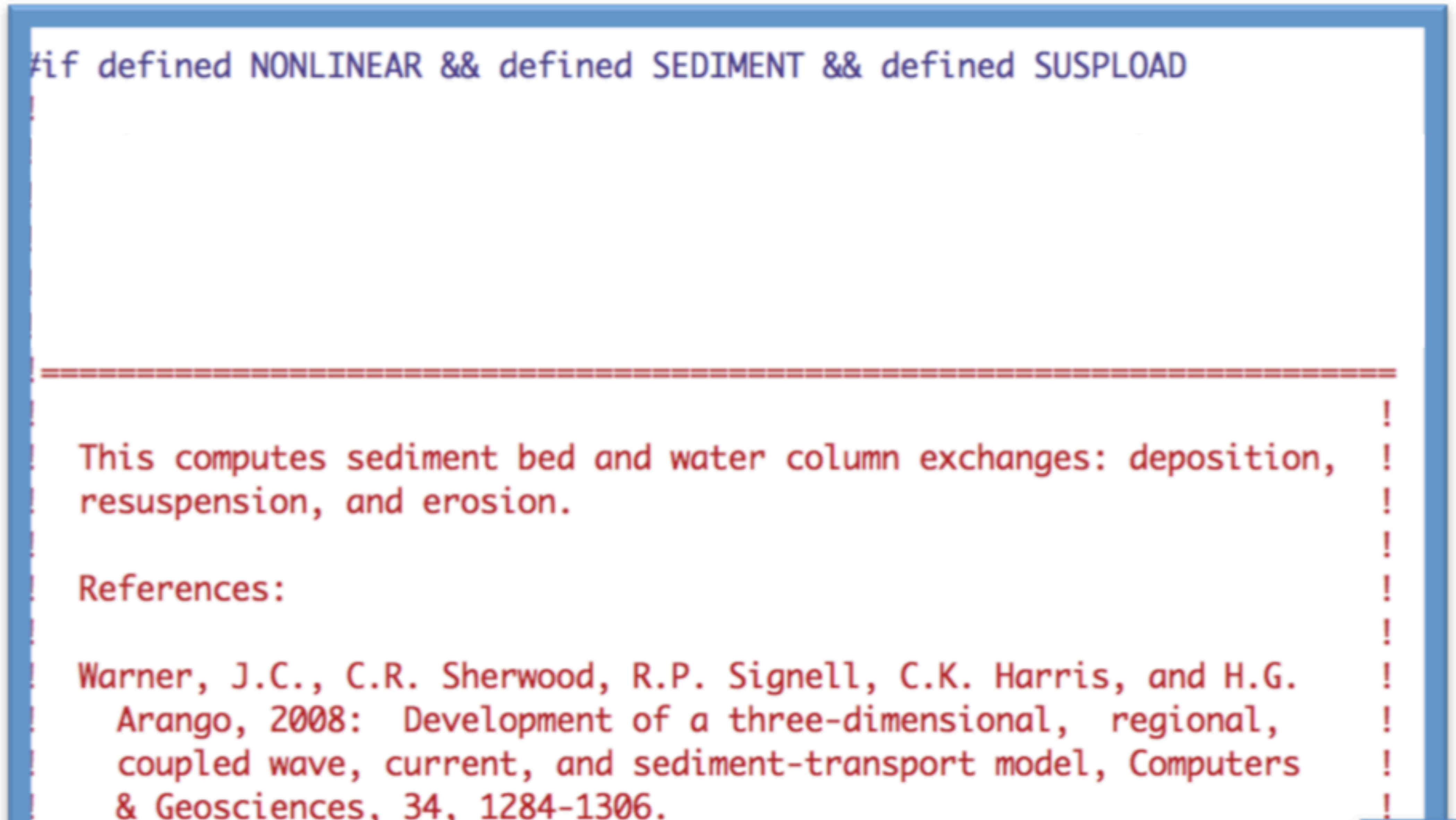


```
#if defined NONLINEAR && defined SEDIMENT && defined SUSPLOAD

!                                                                        !
!  This routine computes the vertical settling (sinking) of suspended   !
!  sediment via a semi-Lagrangian advective flux algorithm. It uses a   !
!  parabolic,  vertical reconstructuin of the suspended  sediment in    !
!  the water column with PPT/WENO constraints to avoid oscillations.    !
!                                                                        !
!  References:                                                           !
!                                                                        !
!  Colella, P. and P. Woodward, 1984: The piecewise parabolic method    !
!    (PPM) for gas-dynamical simulations, J. Comp. Phys., 54, 174-201.  !
!                                                                        !
!  Liu, X.D., S. Osher, and T. Chan, 1994: Weighted essentially         !
!    nonoscillatory shemes, J. Comp. Phys., 115, 200-212.               !
!                                                                        !
!  Warner, J.C., C.R. Sherwood, R.P. Signell, C.K. Harris, and H.G.     !
!    Arango, 2008:  Development of a three-dimensional,  regional,      !
!    coupled wave, current, and sediment-transport model, Computers     !
!    & Geosciences, 34, 1284-1306.                                       !
!                                                                        !
!=======================================================================
```

sed_settling

1. Vertical settling of sediment.
2. Biology routine uses same scheme for particulate classes.
3. Updates concentration fields for vertical settling.
4. Also calculates flux of sediment into the bed.
5. Does the calculations separately for each sediment type.

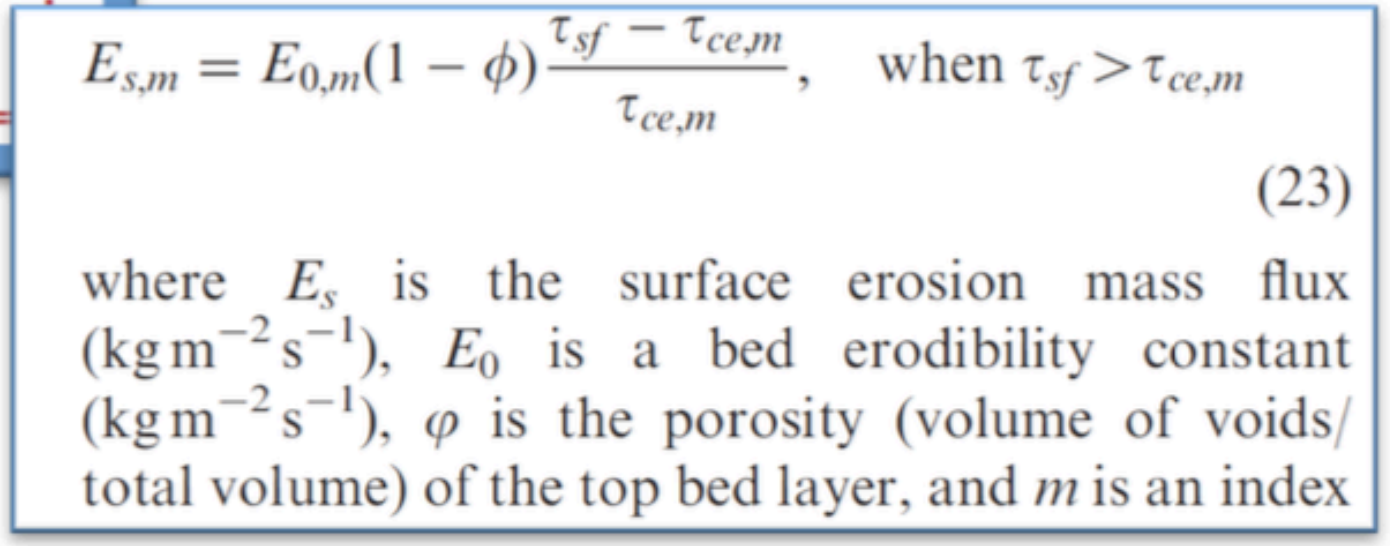
Code structure (6)



```
#if defined NONLINEAR && defined SEDIMENT && defined SUSPLOAD



!=======================================================================
!                                                                      !
!  This computes sediment bed and water column exchanges: deposition,  !
!  resuspension, and erosion.                                          !
!                                                                      !
!  References:                                                         !
!                                                                      !
!  Warner, J.C., C.R. Sherwood, R.P. Signell, C.K. Harris, and H.G.    !
!    Arango, 2008:  Development of a three-dimensional,  regional,     !
!    coupled wave, current, and sediment-transport model, Computers    !
!    & Geosciences, 34, 1284-1306.                                     !
!                                                                      !
!=======================================================================
```

sed_fluxes

1. Exchange of sediment between water column and seabed.
2. First – calculates bed stresses.
3. Calculates erosion based on



$$E_{s,m} = E_{0,m}(1-\phi)\frac{\tau_{sf}-\tau_{ce,m}}{\tau_{ce,m}}, \quad \text{when } \tau_{sf} > \tau_{ce,m} \tag{23}$$

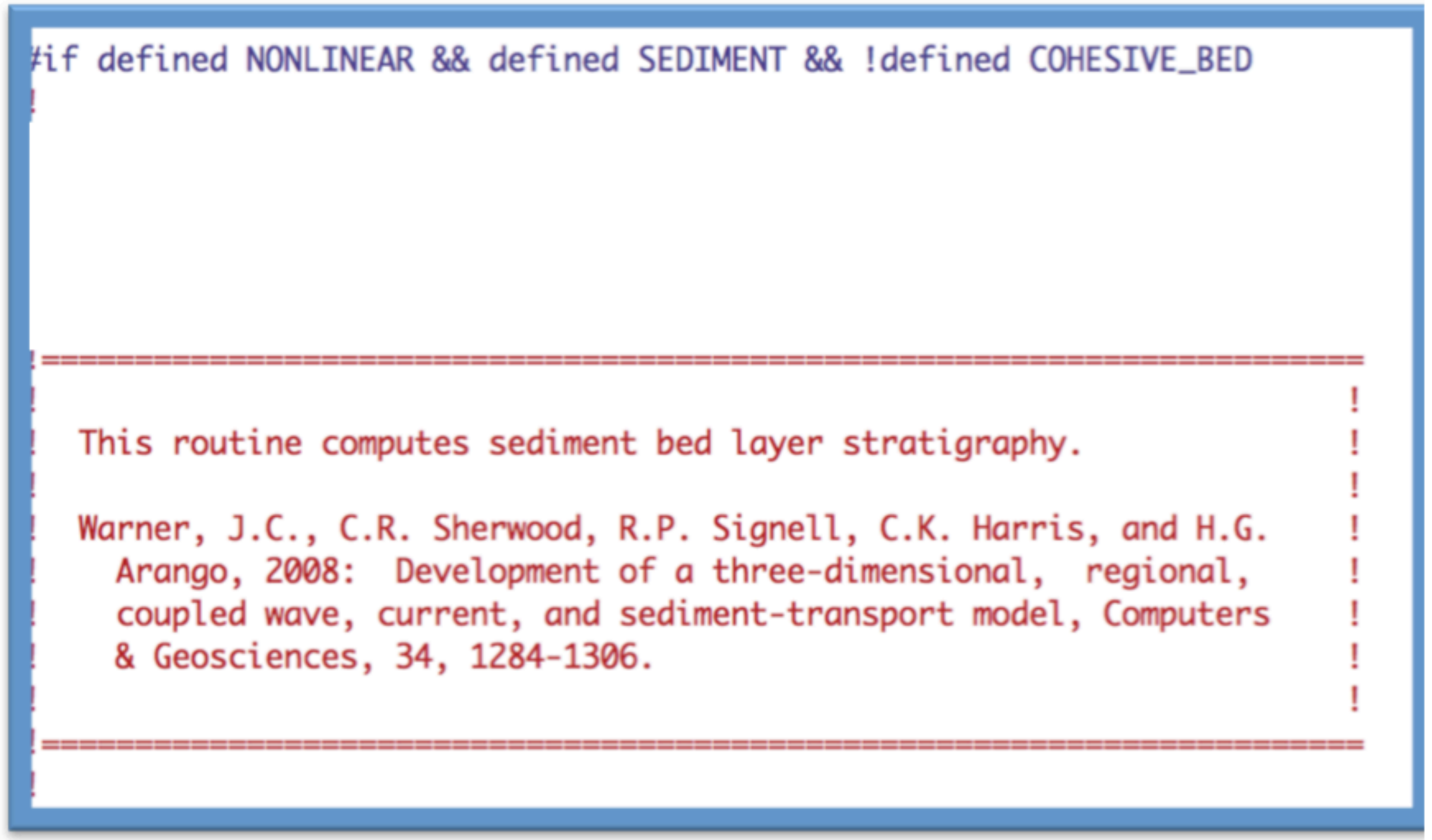
where E_s is the surface erosion mass flux ($\mathrm{kg\,m^{-2}\,s^{-1}}$), E_0 is a bed erodibility constant ($\mathrm{kg\,m^{-2}\,s^{-1}}$), φ is the porosity (volume of voids/total volume) of the top bed layer, and m is an index

4. Erosion limited to amount of each size class in the surface layer + whatever would have settled.
5. The net erosion for each sediment class is called "ero_flux".
6. Updates water column concentration in bottom water layer for the erosion and deposition.

Code structure (7)

sed_bed

1. The longest sediment routine (800 lines).
2. Keeps track of sediment distributions and properties in bed layers.
3. Has net erosion for each sediment class as “ero_flux” from sed_fluxes.F.



```
#if defined NONLINEAR && defined SEDIMENT && !defined COHESIVE_BED
!




!==========================================================================
!                                                                        !
!  This routine computes sediment bed layer stratigraphy.                !
!                                                                        !
!  Warner, J.C., C.R. Sherwood, R.P. Signell, C.K. Harris, and H.G.      !
!    Arango, 2008:  Development of a three-dimensional,  regional,       !
!    coupled wave, current, and sediment-transport model, Computers      !
!    & Geosciences, 34, 1284-1306.                                       !
!                                                                        !
!==========================================================================
!
```

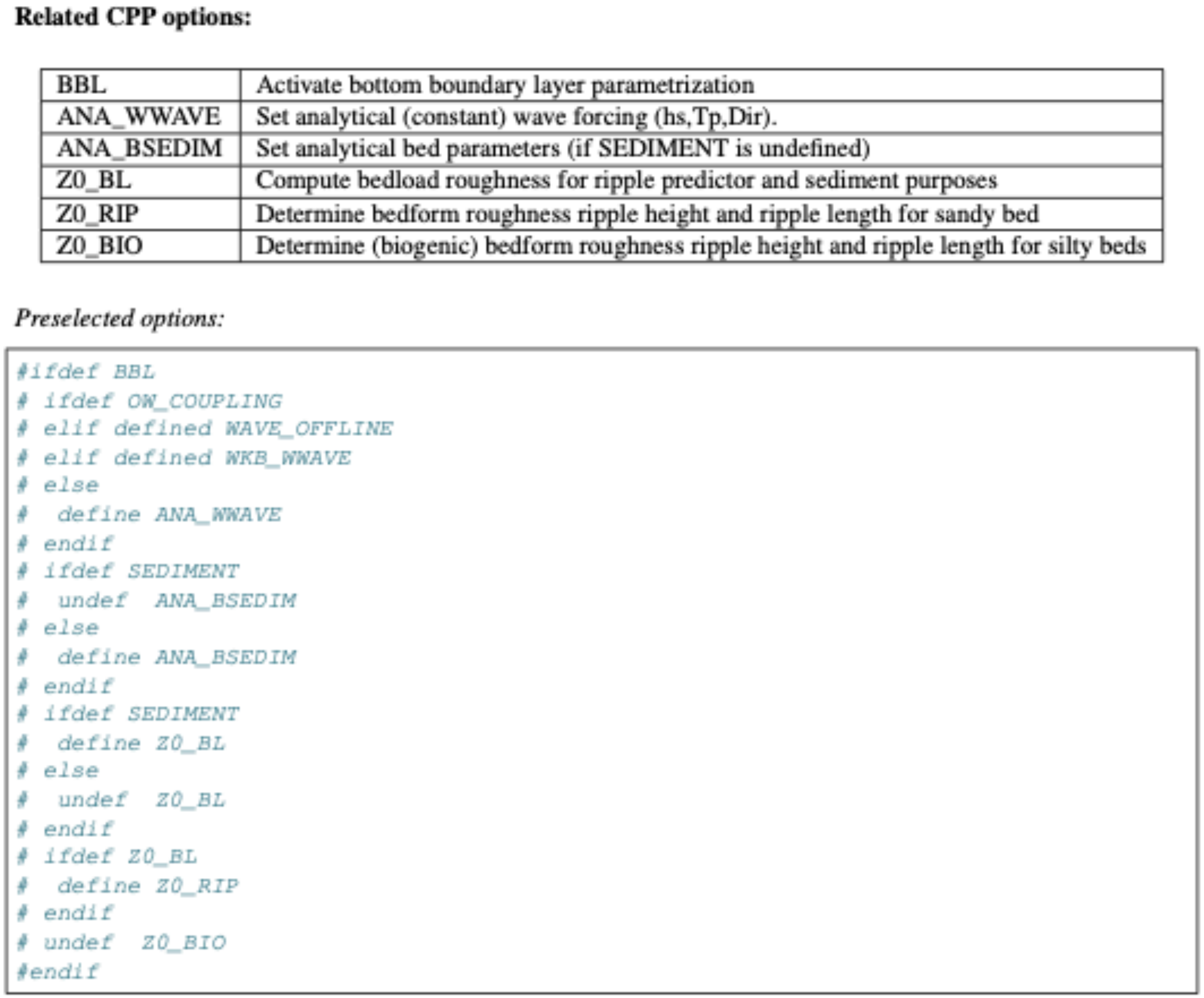
4. Has amount settling to bed as “settling_flux” from sed_settling.F.
5. The net erosion for each sediment class is the difference of “ero_flux” and “settling_flux”.
    1. If “ero_flux – settling_flux” < 0, then you have net deposition of this sediment class. Add sediment to the top layer. When the top layer gets thick, split off a new top layer.
    2. If “ero_flux – settling_flux” > 0, then you have net erosion of this sediment class. Remove sediment from the top layers.
    3. Adjust layers if you needed to add a complete layer or erode one.

IMPLEMENTATION

MODEL OPTIONS

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:

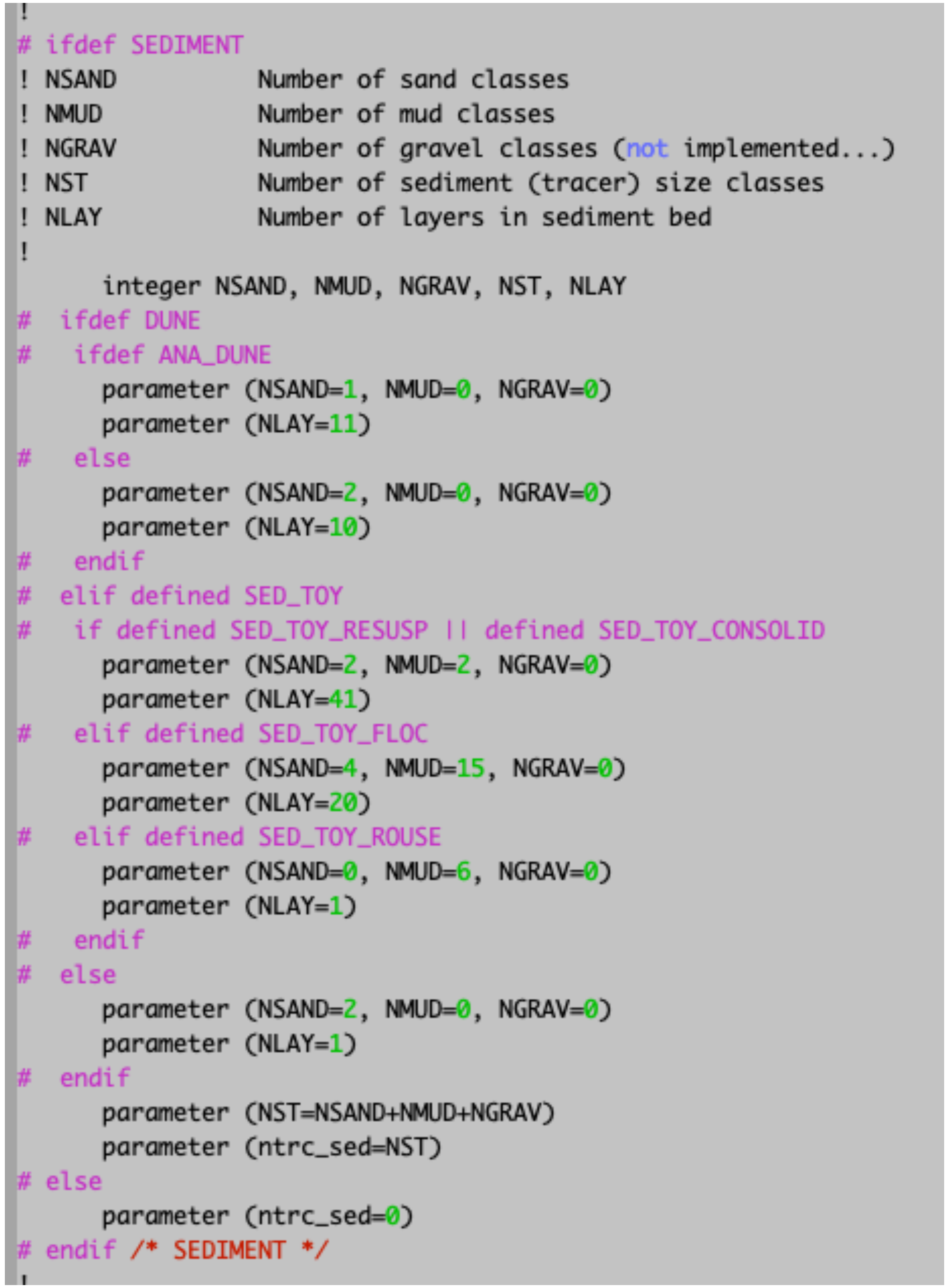
```
#ifdef BBL
# ifdef OW_COUPLING
# elif defined WAVE_OFFLINE
# elif defined WKB_WWAVE
# else
#  define ANA_WWAVE
# endif
# ifdef SEDIMENT
#  undef  ANA_BSEDIM
# else
#  define ANA_BSEDIM
# endif
# ifdef SEDIMENT
#  define Z0_BL
# else
#  undef  Z0_BL
# endif
# ifdef Z0_BL
#  define Z0_RIP
# endif
#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

Model options

Sediment parameters

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

=> in param.h



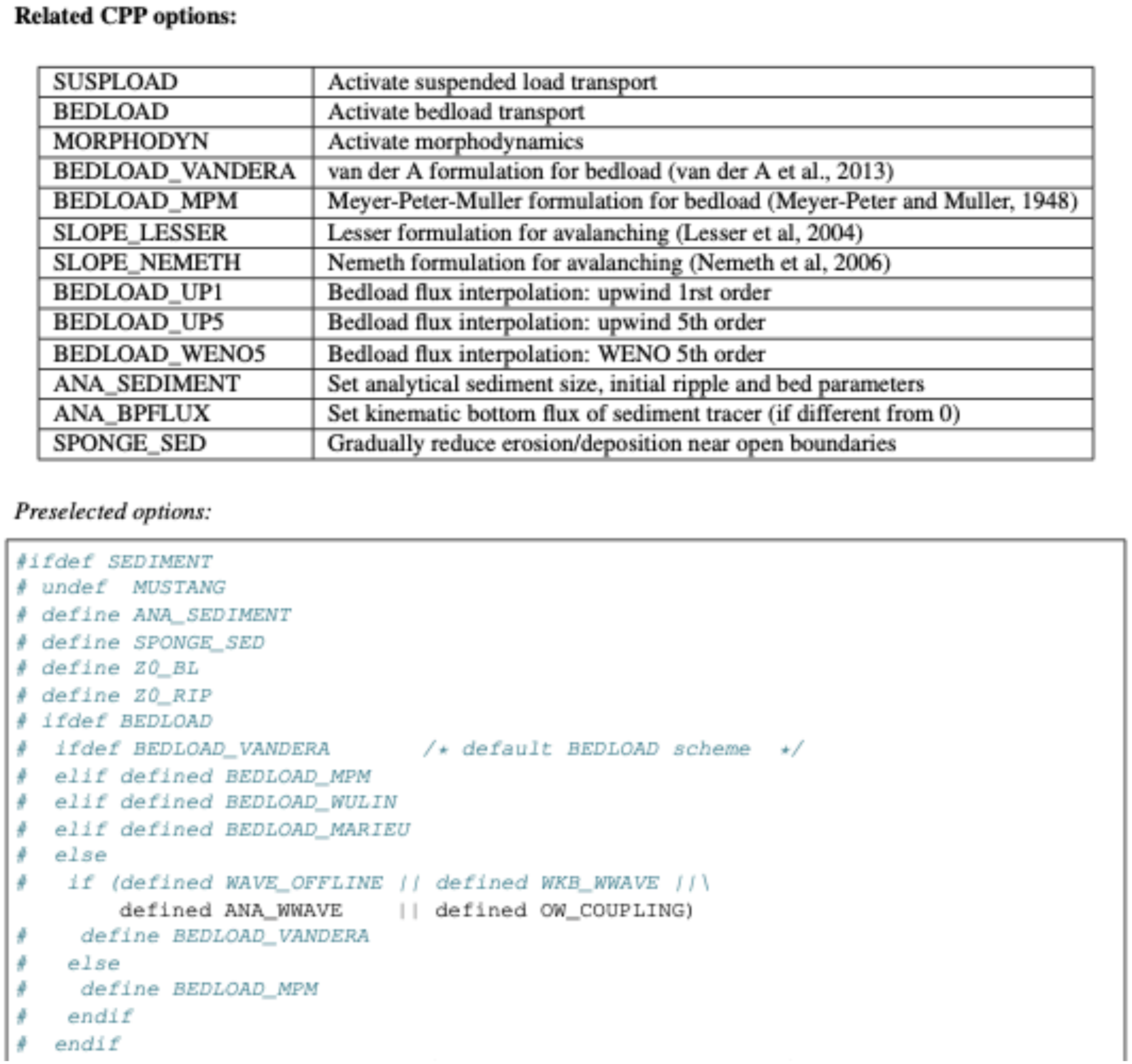
```
!
# ifdef SEDIMENT
! NSAND           Number of sand classes
! NMUD            Number of mud classes
! NGRAV           Number of gravel classes (not implemented...)
! NST             Number of sediment (tracer) size classes
! NLAY            Number of layers in sediment bed
!
      integer NSAND, 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 or MUSTANG
  - 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:

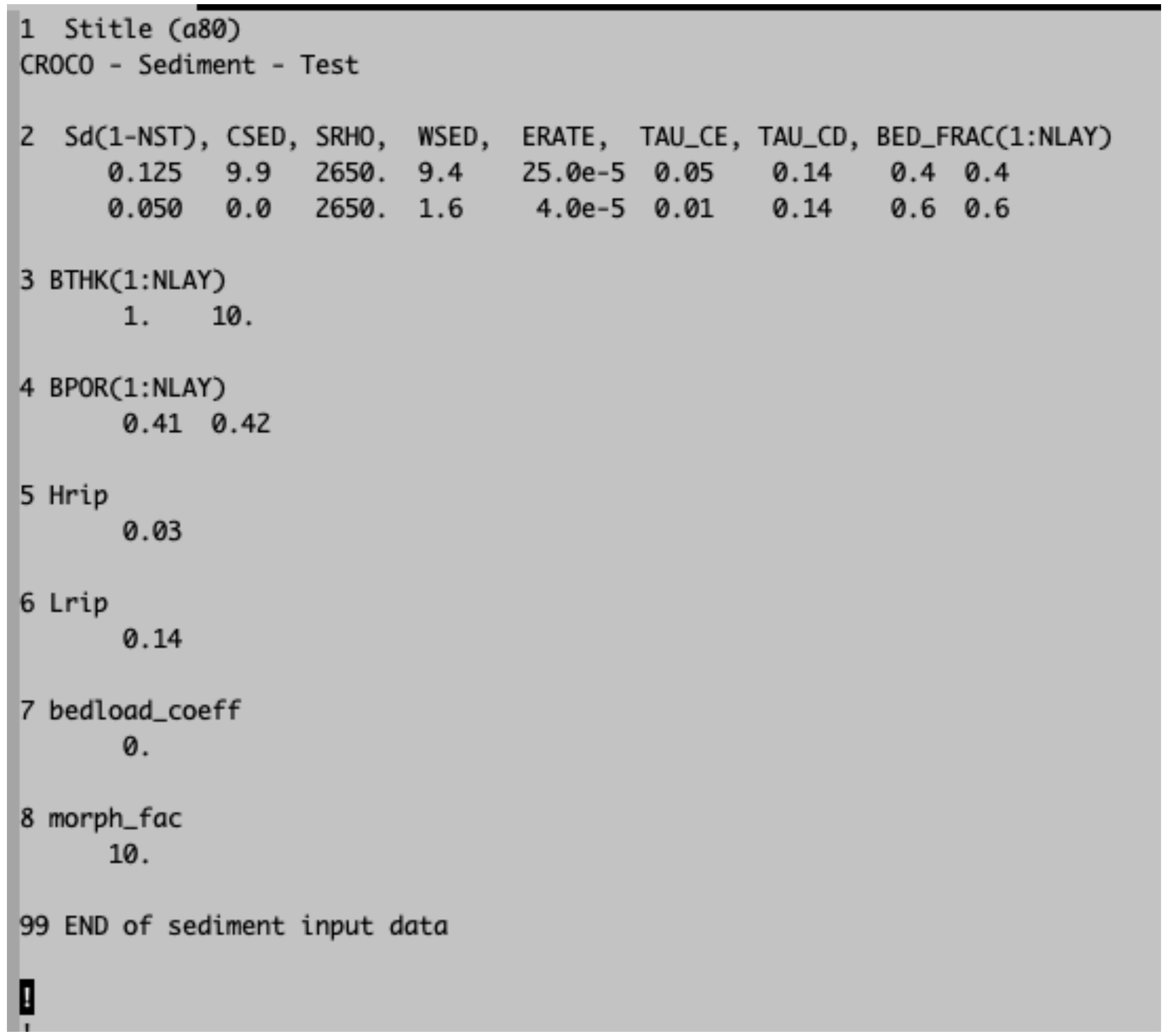
```
#ifdef SEDIMENT
# undef  MUSTANG
# define ANA_SEDIMENT
# define SPONGE_SED
# define Z0_BL
# define Z0_RIP
# ifdef BEDLOAD
#  ifdef BEDLOAD_VANDERA       /* default BEDLOAD scheme  */
#  elif defined BEDLOAD_MPM
#  elif defined BEDLOAD_WULIN
#  elif defined BEDLOAD_MARIEU
#  else
#   if (defined WAVE_OFFLINE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

Model options

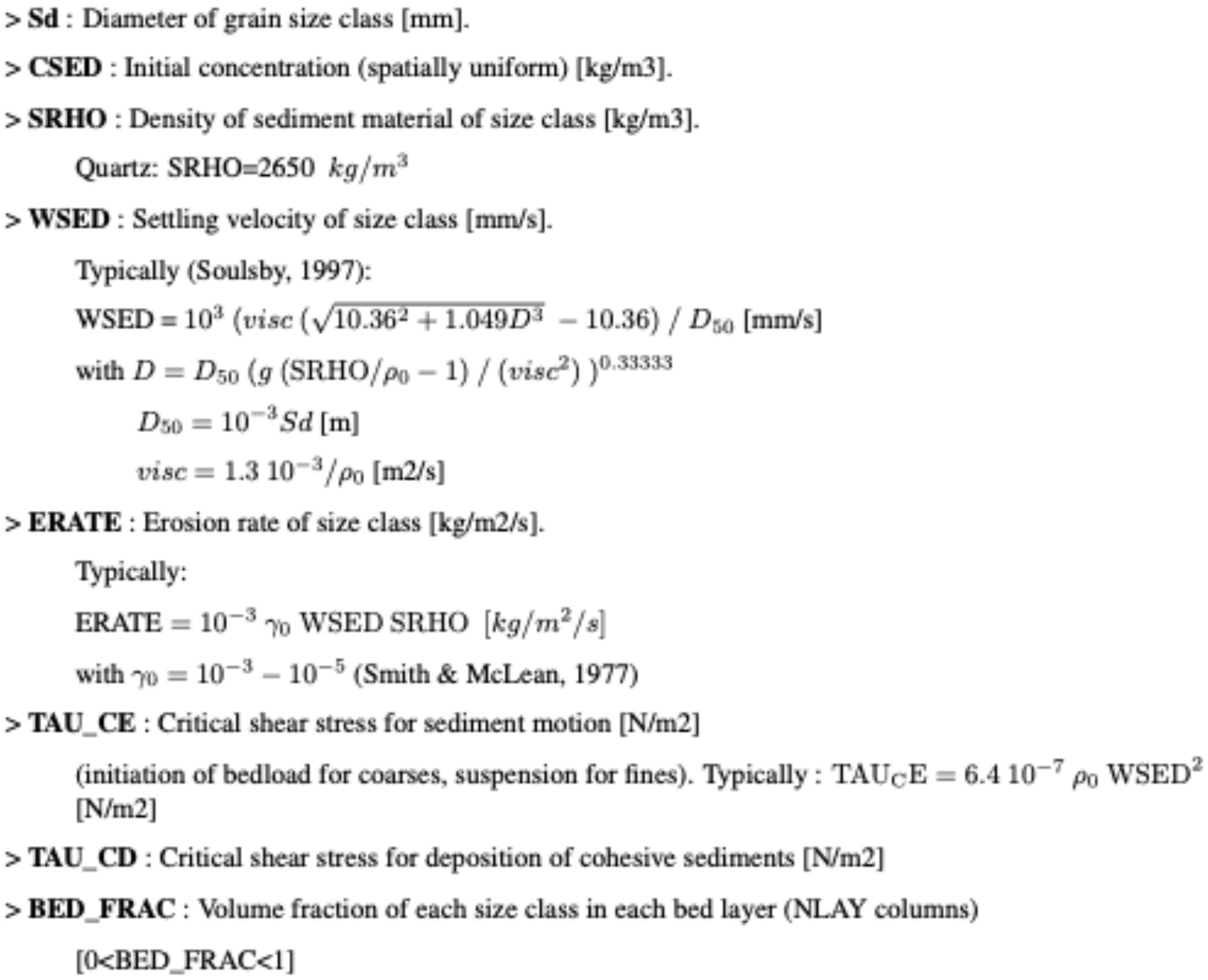
Input file

- Additional file at run time : sediment.in

  Consistent with :
  - 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:

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

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 : $\mathrm{TAU_CE} = 6.4\ 10^{-7}\ \rho_0\ \mathrm{WSED}^2$ [N/m2]

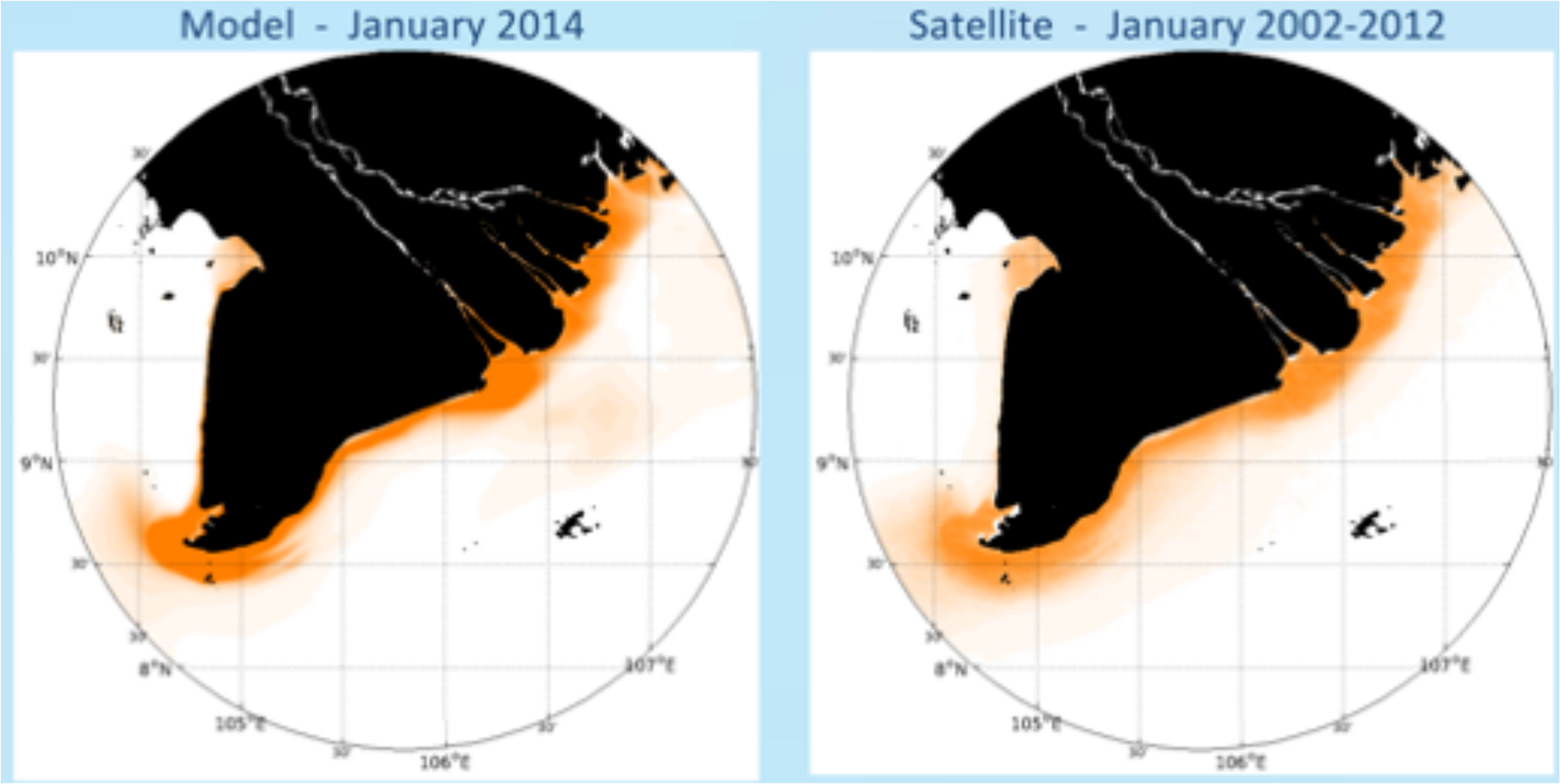
> **TAU_CD** : Critical shear stress for deposition of cohesive sediments [N/m2]

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

[0<BED_FRAC<1]

EXAMPLES

EXAMPLE 1

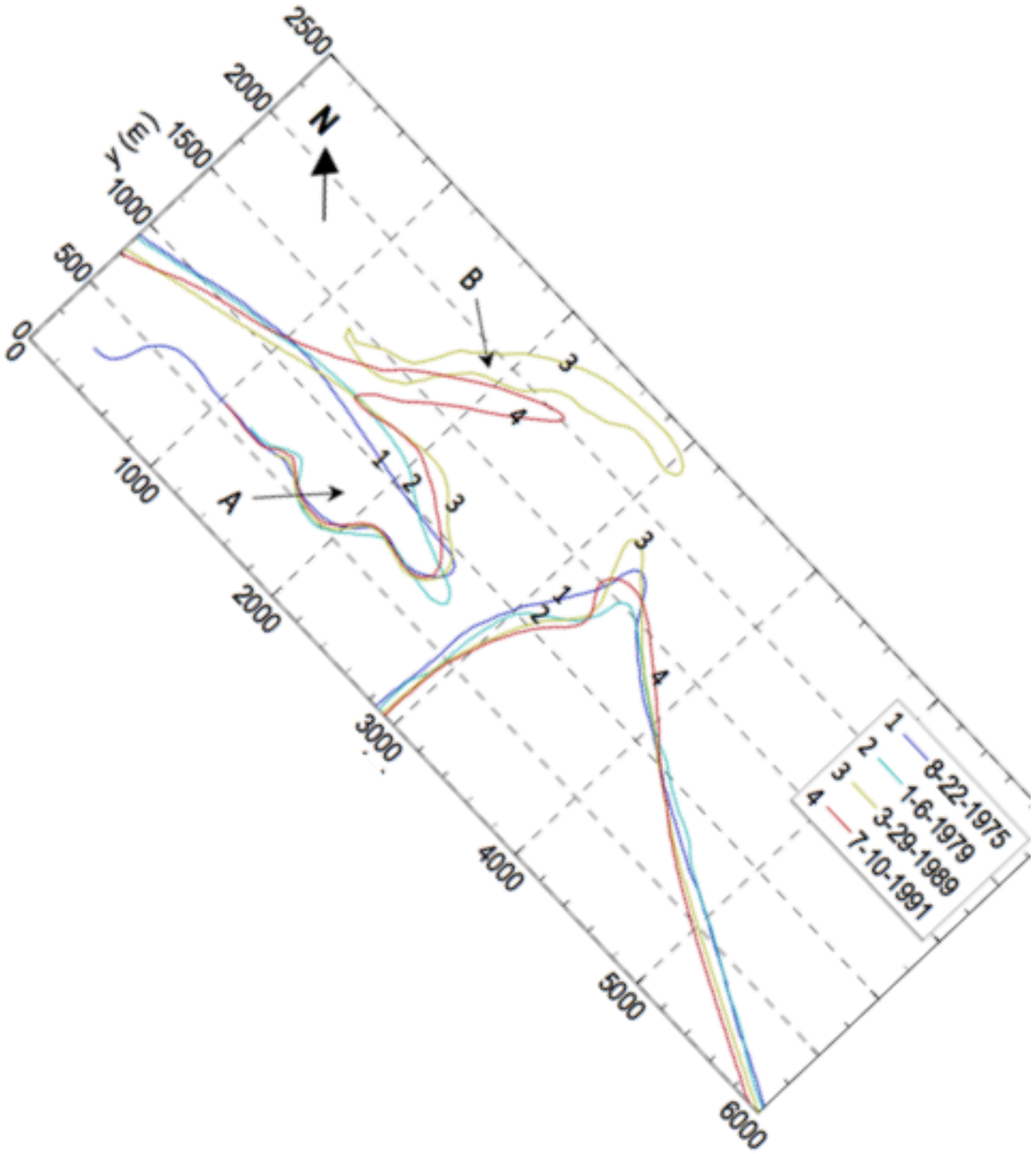

Model - January 2014

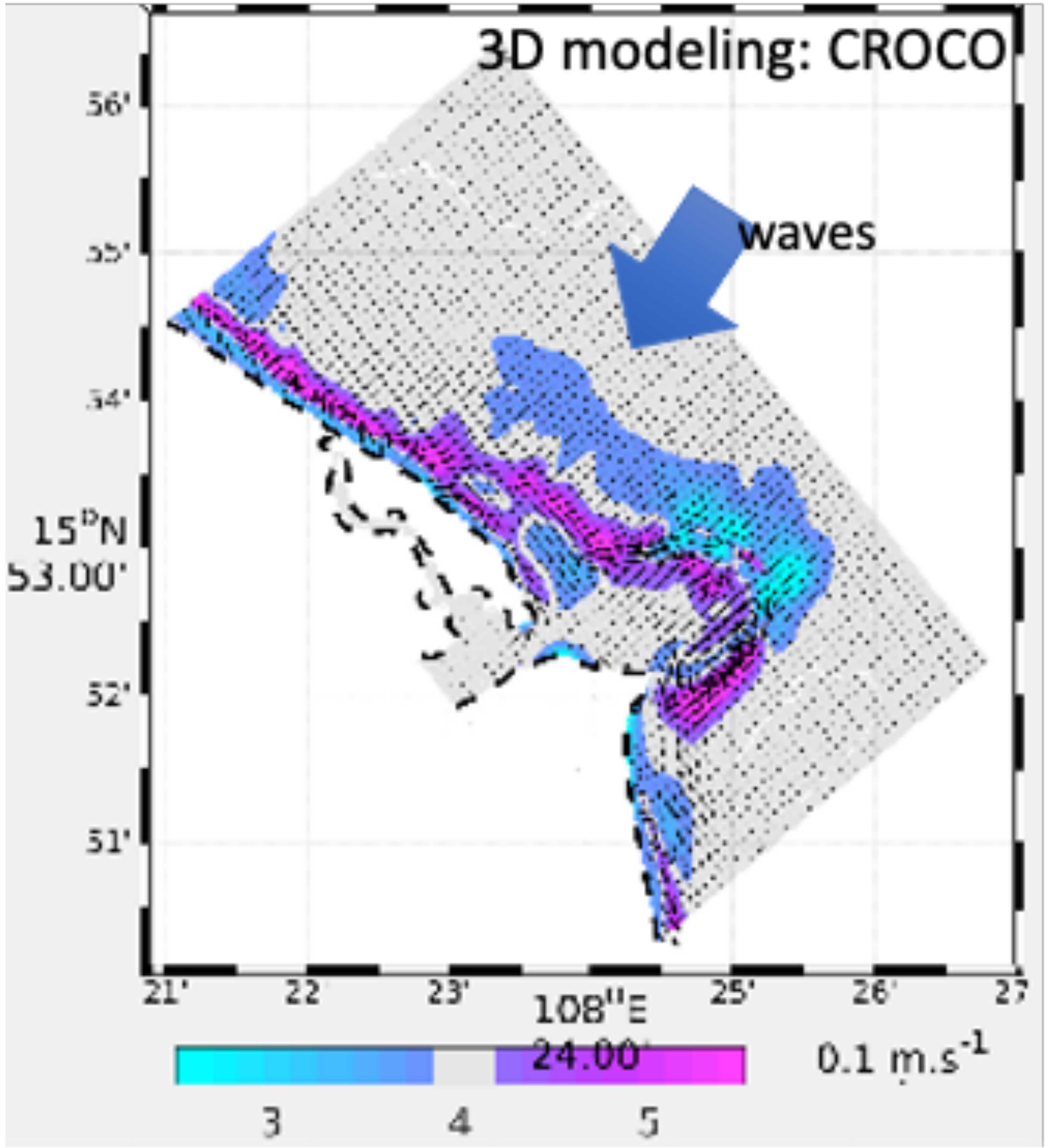
Satellite - January 2002-2012

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

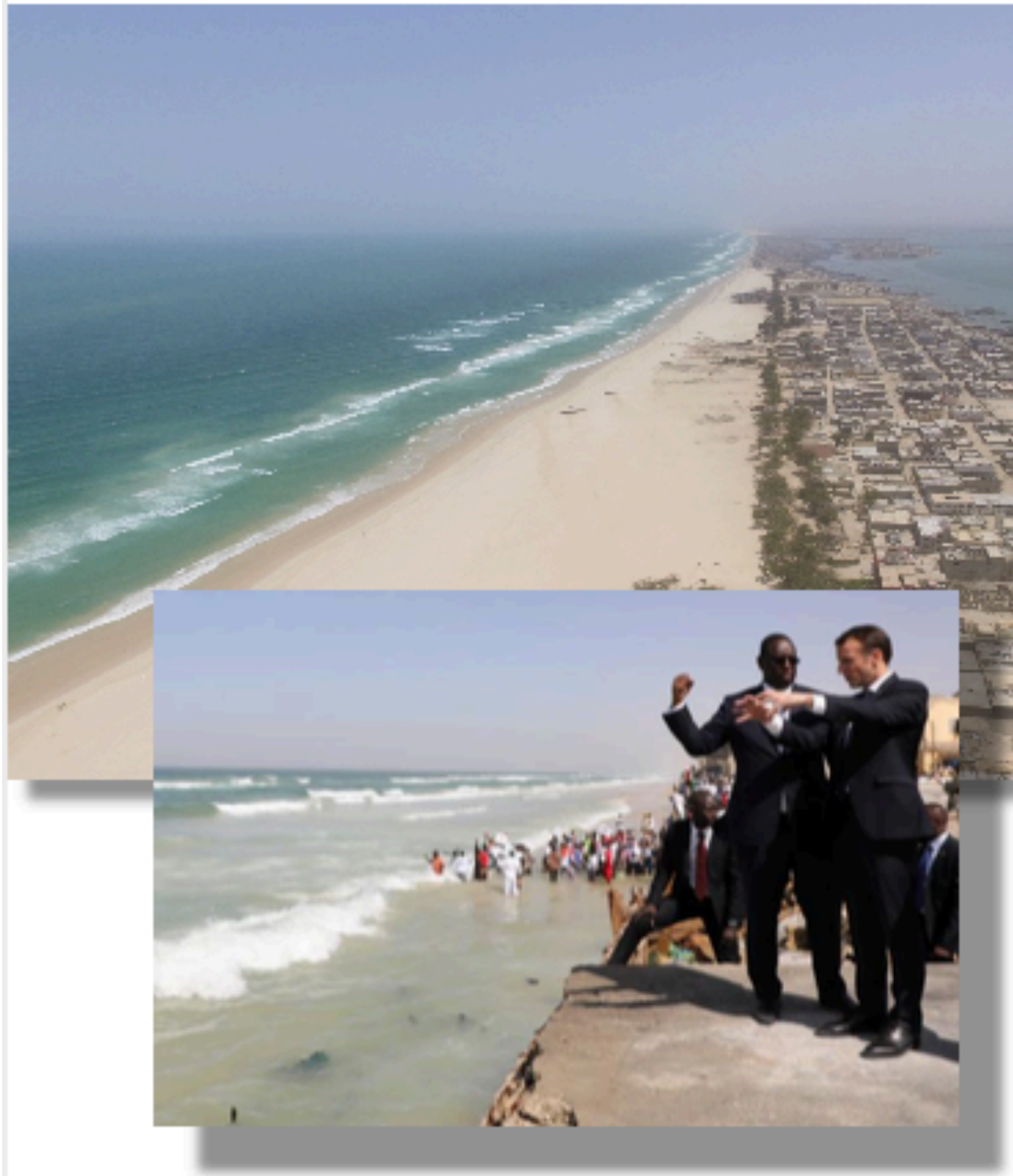
EXAMPLE 2

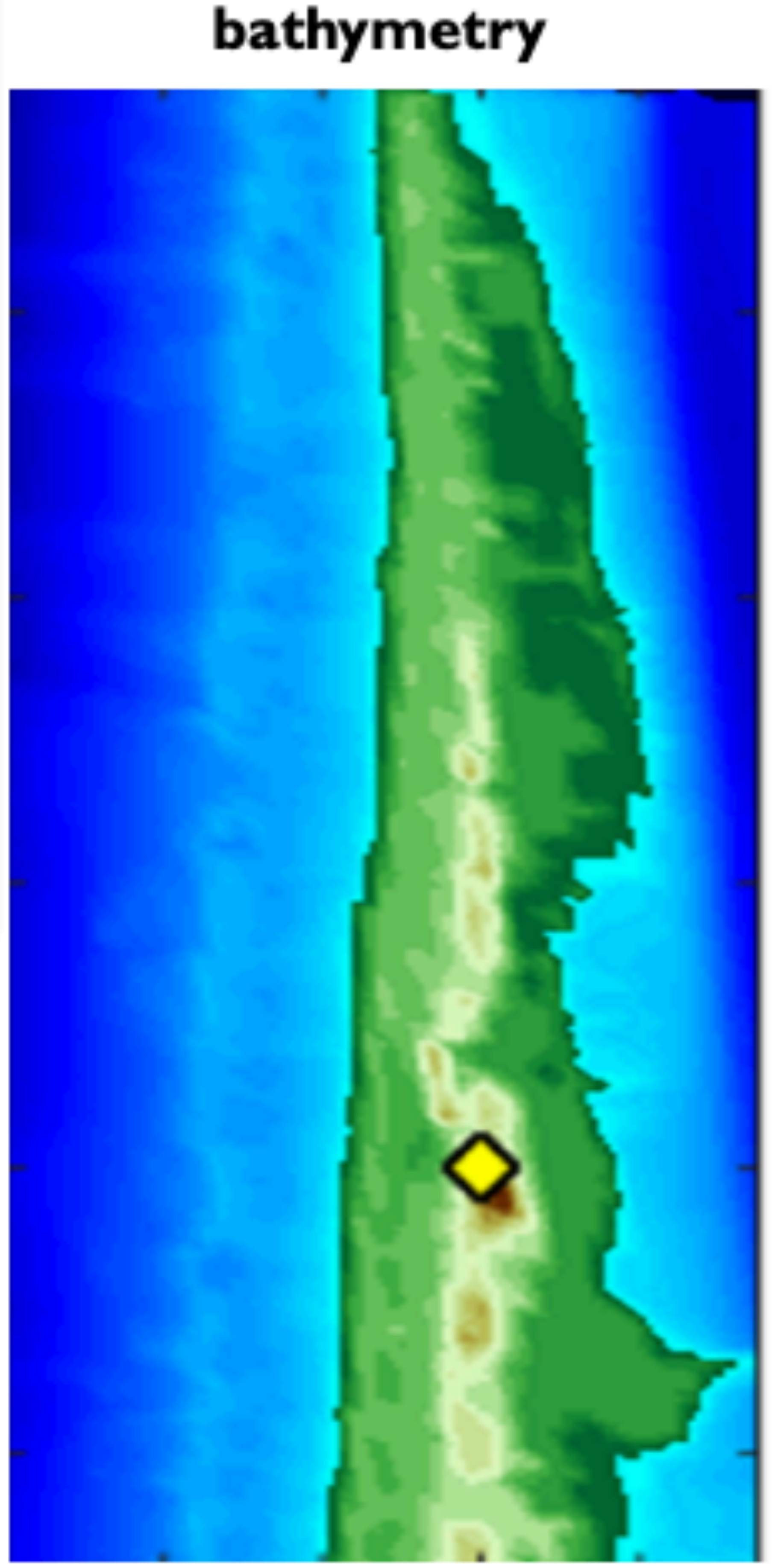

Hanoi

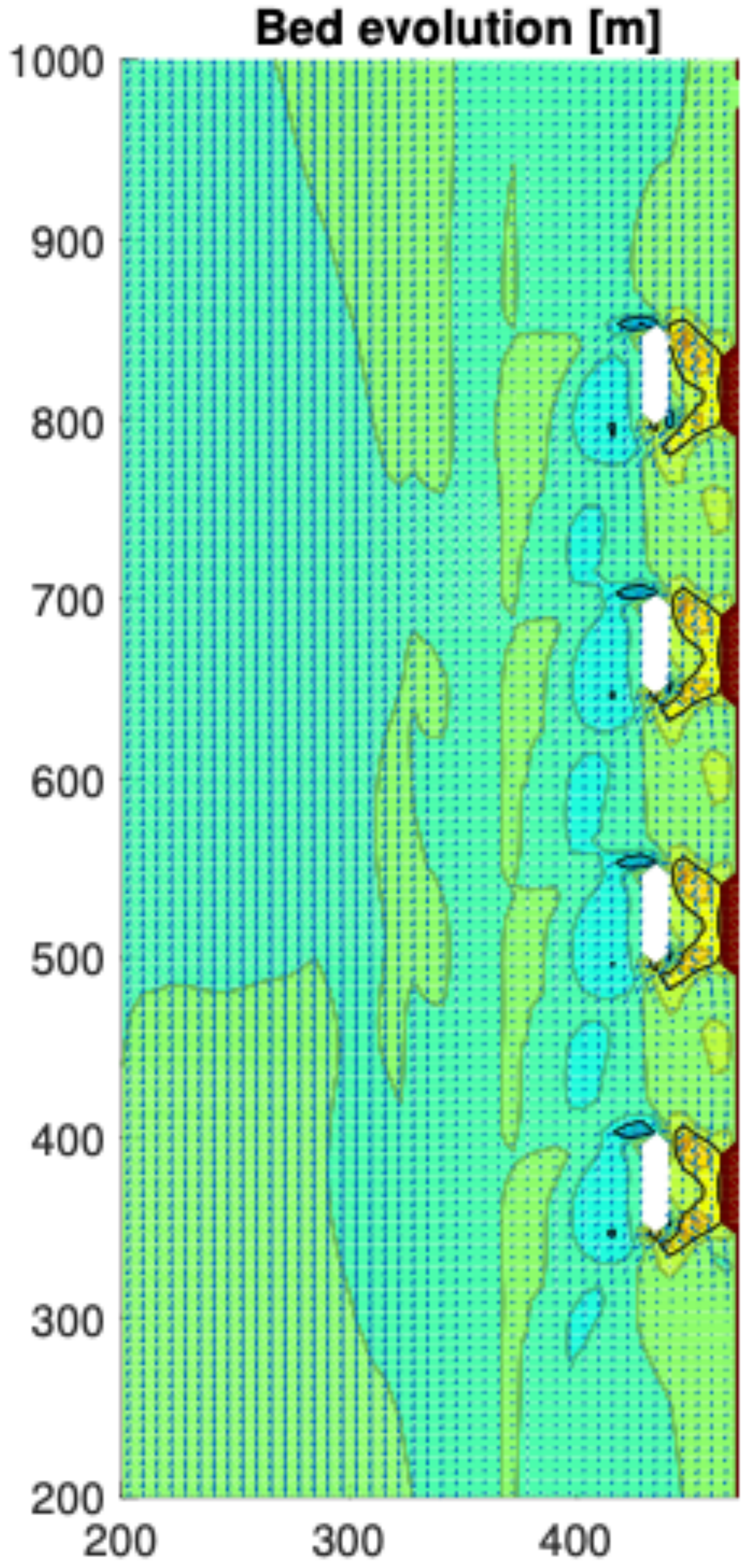

2500
2000
1500
1000
500
0
y (m)
N
B
A
1
2
3
4
0
1000
2000
3000
4000
5000
6000
1 8-22-1975
2 1-6-1979
3 3-29-1989
4 7-10-1991


3D modeling: CROCO
waves
56'
55'
54'
15°N
53.00'
52'
51'
21'
22'
23'
108°E
24.00'
25'
26'
27'
0.1 m.s-1
3
4
5

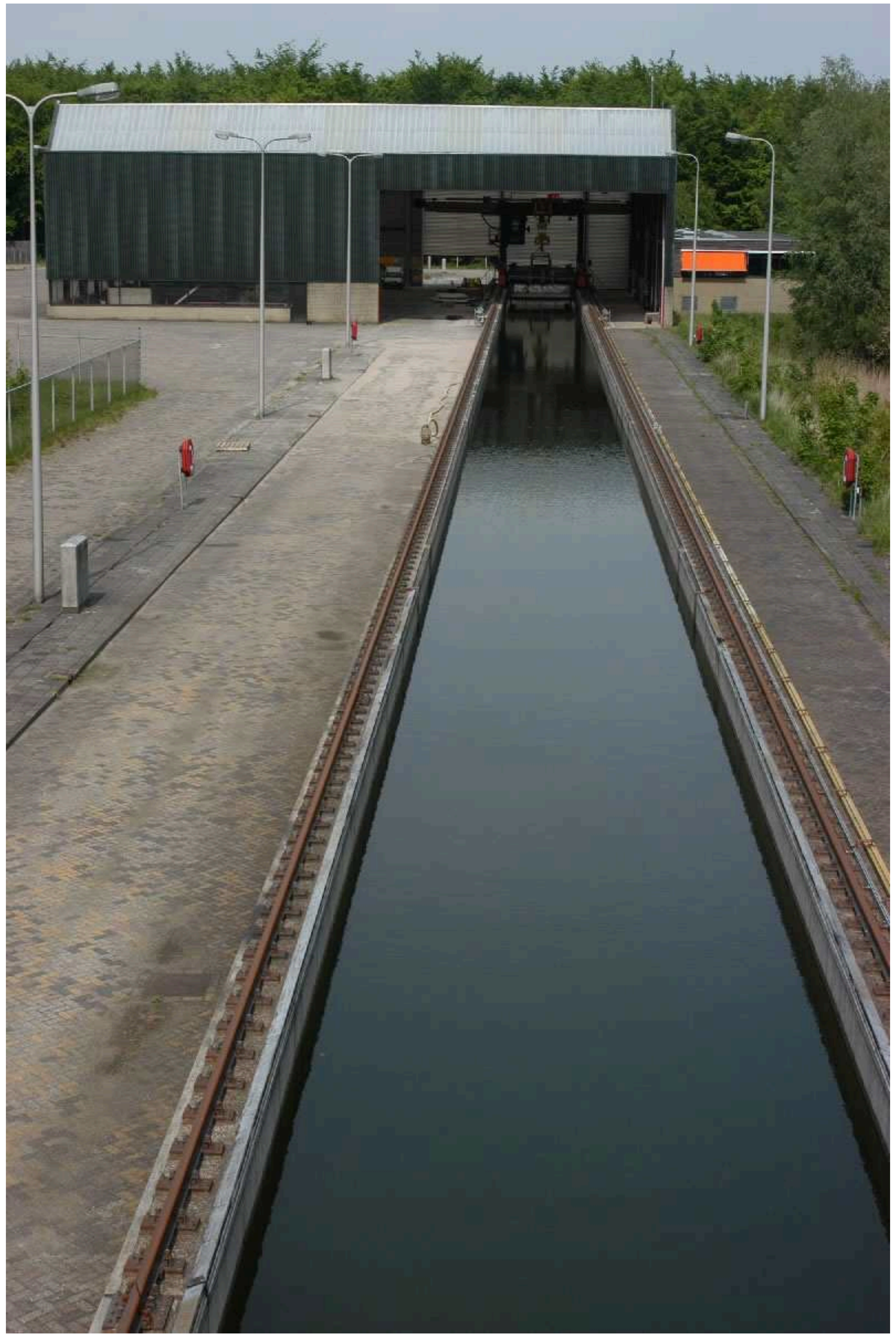
EXAMPLE 3

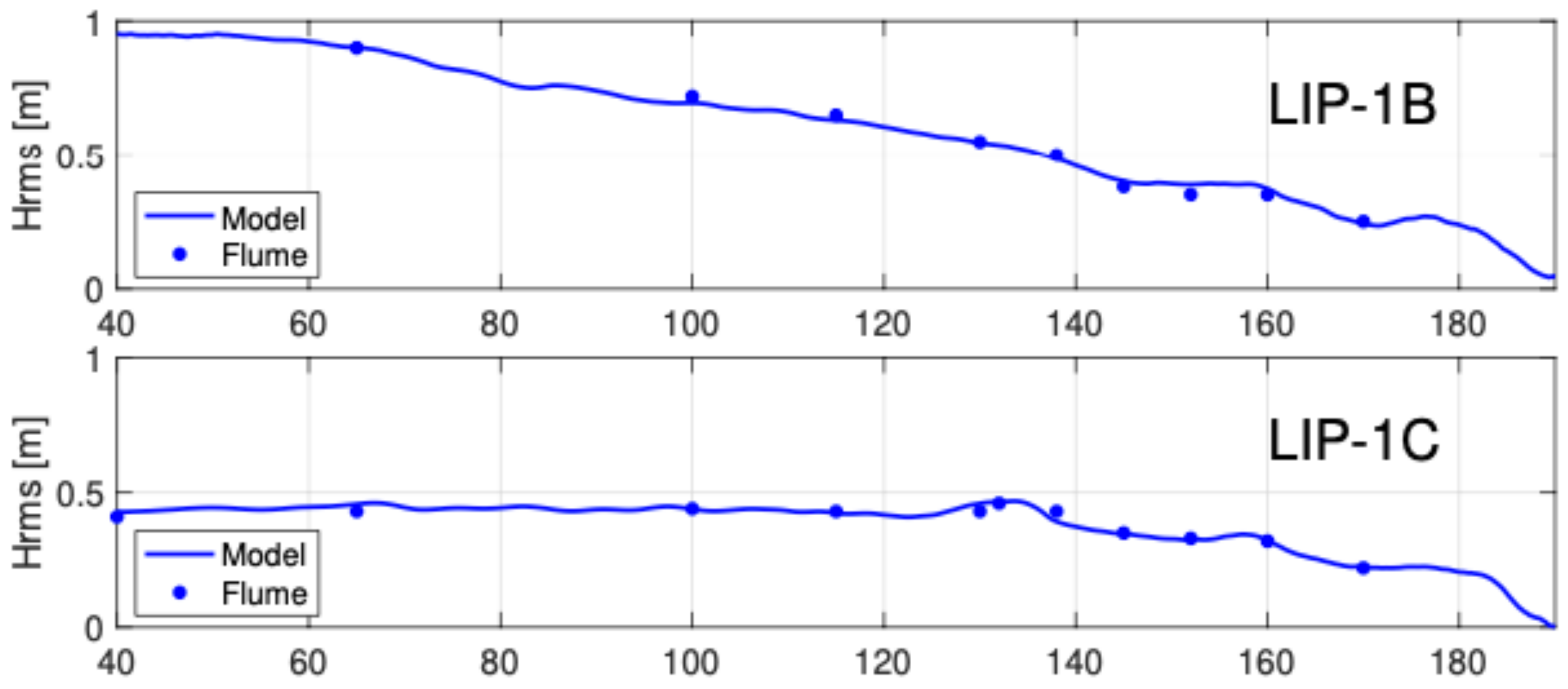


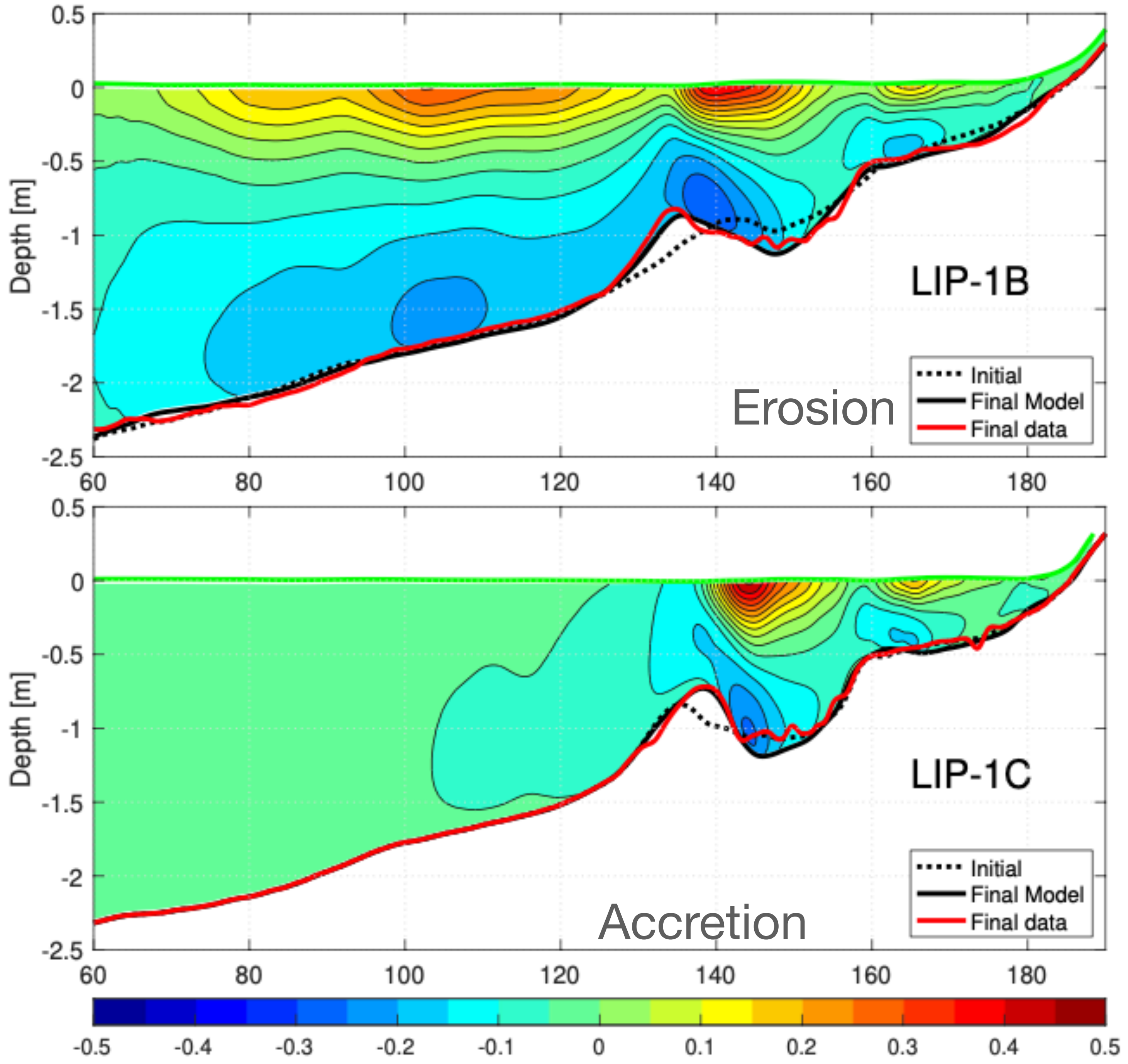

bathymetry

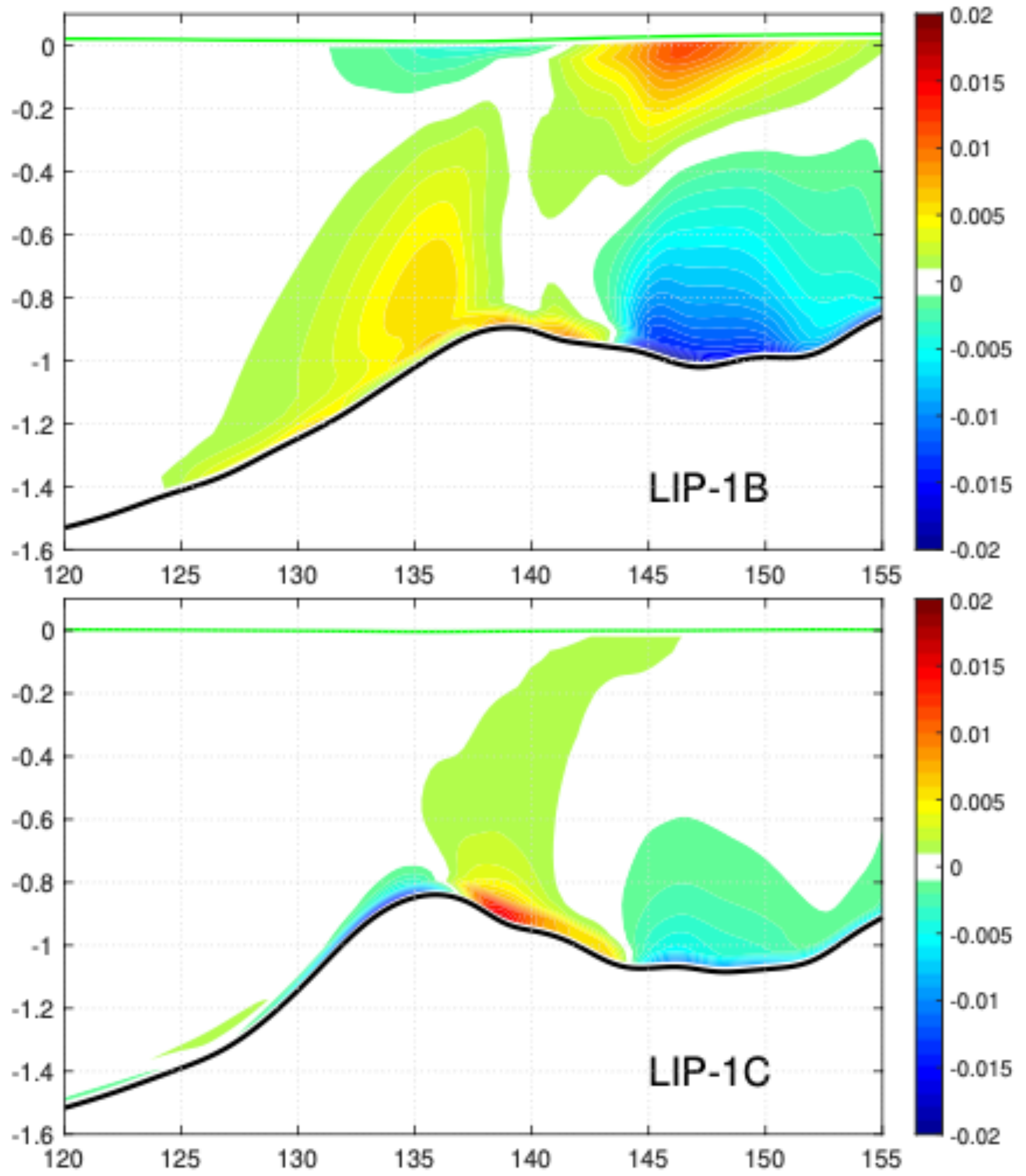

Bed evolution [m]
1000
900
800
700
600
500
400
300
200
200
300
400

EXAMPLE 4




LIP-1B
Hrms [m]
Model
Flume
0
0.5
1
40
60
80
100
120
140
160
180
LIP-1C
Hrms [m]
Model
Flume


LIP-1B
Depth [m]
Erosion
Initial
Final Model
Final data
0.5
0
-0.5
-1
-1.5
-2
-2.5
60
80
100
120
140
160
180
LIP-1C
Depth [m]
Accretion
Initial
Final Model
Final data
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5


LIP-1B
LIP-1C
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
120
125
130
135
140
145
150
155
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02

SUMMARY

Currently

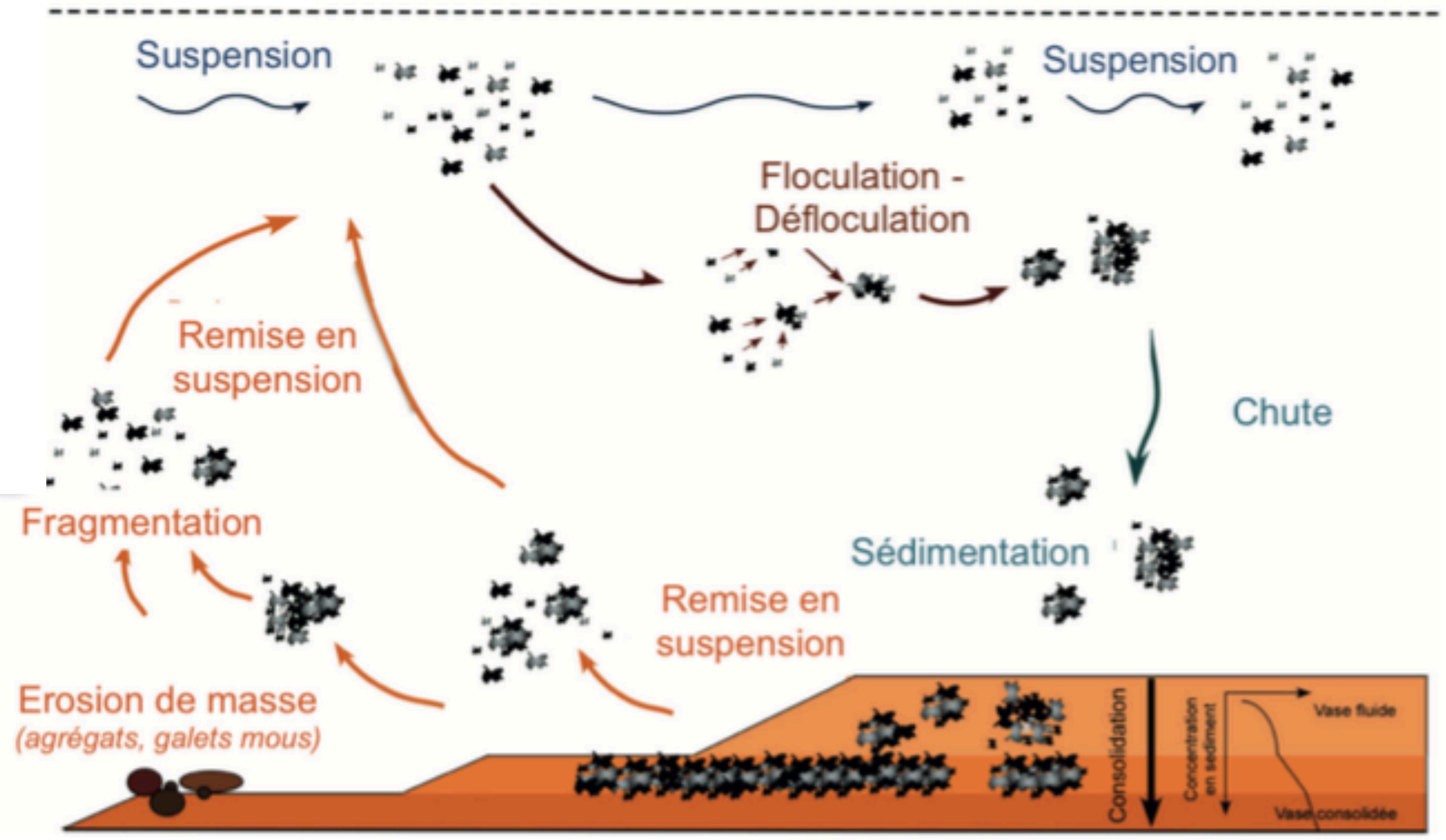
- Increasing effort
- Focus on sandy/wave dominated environment
- More and more confident
- Wave resolved configurations !

Underway

- consolidation
- floculation

TBD

- interaction with vegetation
- bio diffusion
- Effect on density



Floculation

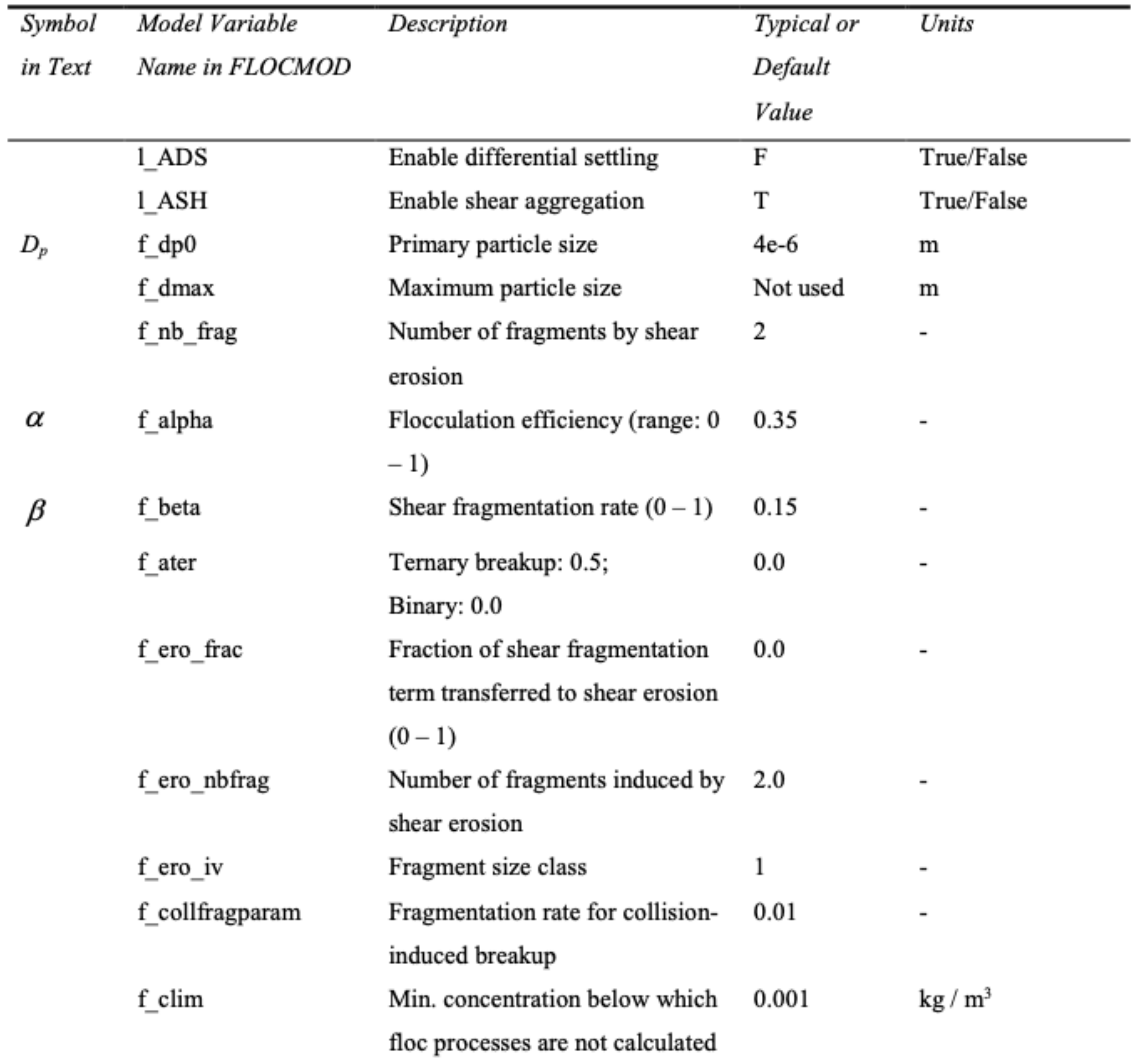
- FLOCMOD
- Nombre de classes constant avec transfert entre classes

$$\frac{dN(k)}{dt} = G_a(k) + G_{bs}(k) + G_{bc}(k) - L_a(k) - L_{bs}(k) - L_{bc}(k)$$

Tous les sédiments cohésifs sont traités comme des flocs avec un diamètre caractéristique

Agrégation par collision : cisaillement ou vitesse de chute
Désagrégation par collision ou turbulence

Différentes fonctions de redistribution



Symbol in Text	*Model Variable Name in FLOCMOD*	*Description*	*Typical or Default Value*	*Units*
	l_ADS	Enable differential settling	F	True/False
	l_ASH	Enable shear aggregation	T	True/False
D_p	f_dp0	Primary particle size	4e-6	m
	f_dmax	Maximum particle size	Not used	m
	f_nb_frag	Number of fragments by shear erosion	2	-
α	f_alpha	Flocculation efficiency (range: 0 – 1)	0.35	-
β	f_beta	Shear fragmentation rate (0 – 1)	0.15	-
	f_ater	Ternary breakup: 0.5; Binary: 0.0	0.0	-
	f_ero_frac	Fraction of shear fragmentation term transferred to shear erosion (0 – 1)	0.0	-
	f_ero_nbfrag	Number of fragments induced by shear erosion	2.0	-
	f_ero_iv	Fragment size class	1	-
	f_collfragparam	Fragmentation rate for collision-induced breakup	0.01	-
	f_clim	Min. concentration below which floc processes are not calculated	0.001	kg / m^3