Coastal hydrodynamics and morphodynamics

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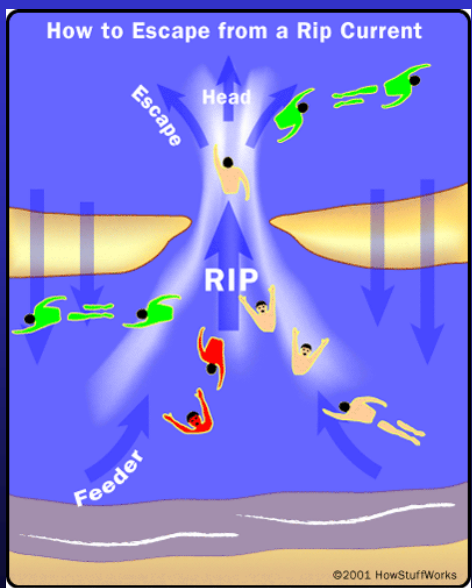
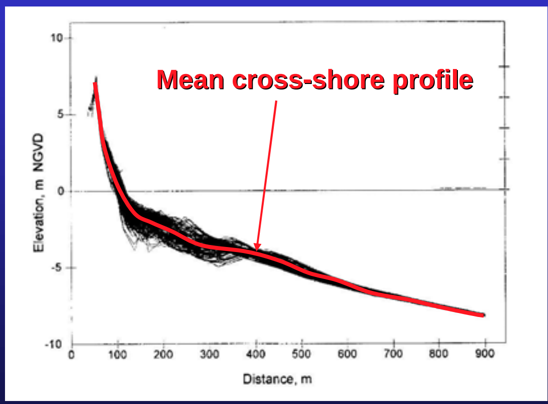
Rip currents cause many casualities each year



Many sandy coasts are characterized by

• mean cross-shore bottom profile

(mean = alongshore + time-average)



Duck (NC)

+ rhythmic bottom patterns

(cross-shore/longshore)

'Non-trivial' / rhythmic topography :

Example 1: <u>longshore bars in the surfzone</u>

ARGUS video system

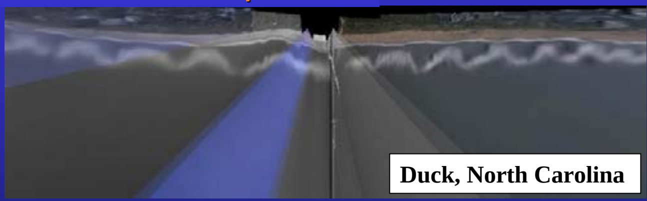
panorama image
Noordwijk

Cross-shore length scale ~ 100 m
Generation timescale ~ months-years

Example 2: rhythmic bar patterns in the surfzone

Many complex patterns are alongshore rhythmic:

Crescentic bar and rip channels



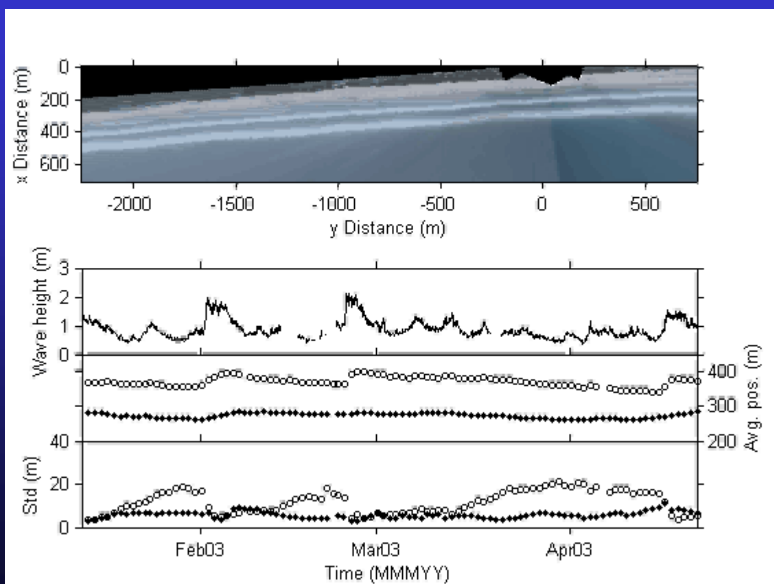
Shore-oblique bars

Truc Vert Beach,
Atlantic French Coast

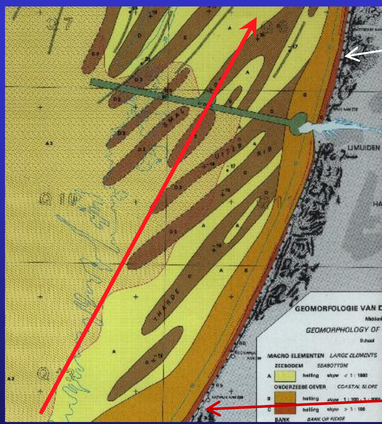
alongshore length scales:
~ 100 - 1000 m

time scale: days - weeks

Variability of sand banks (Gold Coast, Australia)



Example 3: shoreface-connected ridges on the inner shelf



Egmond

bathymetric map
Dutch coastal zone

red arrow : direction
of storm-driven flow

Noordwijk

- ridges observed in depths of 10-20 m
- alongshore length scale: ~ 5 km
- migrate northward: ~ 2 m/yr
- heights: 1-6 m
- crests: 'upcurrent' orientation
- time scale: centuries

Objectives of this presentation:

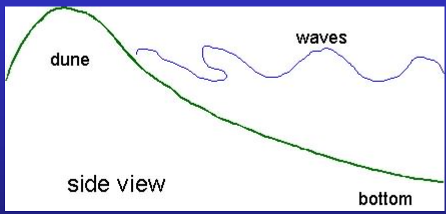
1. Discuss models that yield fundamental knowledge about
   - stability properties of equilibrium beach profiles
     (↔ formation of bars and sand ridges)
   - characteristics of bars and ridges
     (time scale, migration, spatial pattern, grain sorting)
   - finite-amplitude behavior (saturation?)

2. tools to address practical problems, e.g.
   - morphodynamic response to human interventions
     (e.g. sand mining, dredging navigation channels,
     beach nourishment, construction of harbors, seawalls…)
   - ………….

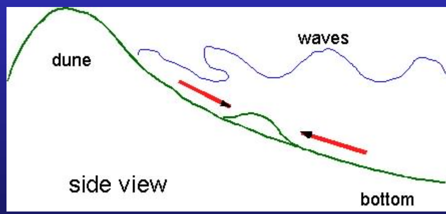
Main message:

formation of many bars/ridges is due to <u>self-organization</u>

(i.e., inherent instabilities of the coupled water-bottom system)



equilibrium



perturbation =>

net sediment transport (red arrows)
here positive feedback: <u>growth</u>

spatial/temporal scales of bars/ridges uncorrelated with external forcing

Procedure:

1. Formulation of a <u>model</u> :

   water motion ← bottom evolution

   water motion → sediment transport → bottom evolution

   Here: idealized = straight coast, forcing alongshore uniform
   limited number of physical processes + simplified description

2. Find an <u>equilibrium state</u>

3. Perform <u>linear stability analysis</u>
   dynamics of small perturbations, arbitrary scales, do they grow?

   Each perturbation -> growth rate

   mode with the largest growth rate: <u>the preferred mode</u>
   => spatial pattern, migration speed, growth time scale

4. Perform <u>nonlinear (stability) analysis</u>
   finite-amplitude behaviour of bars and ridges

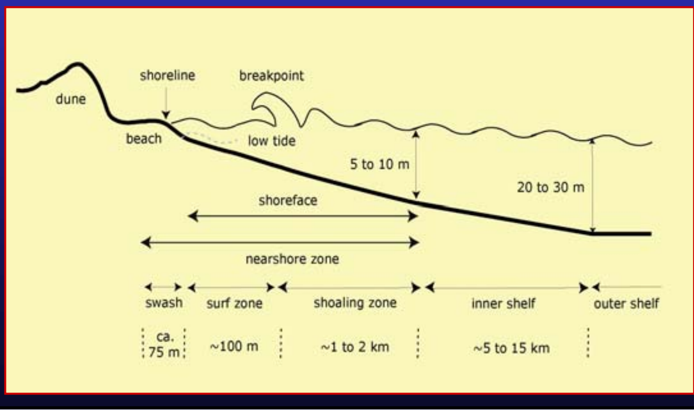
Forthcoming topics:

A. Inner shelf dynamics

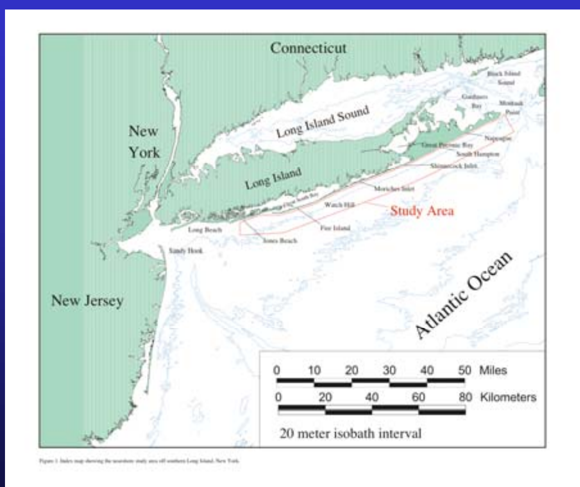
(shoreface-connected ridges: formation and saturation)

B. Surf zone dynamics (very brief)

(alongshore rhythmic bars: formation and saturation)

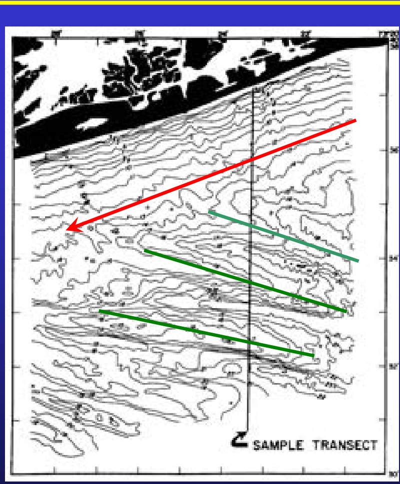


Topic A: shoreface-connected sand ridges (sfcr)



Long Island (USA)

Topic A: shoreface-connected sand ridges (sfcr)



Long Island (USA)

ridges: green lines

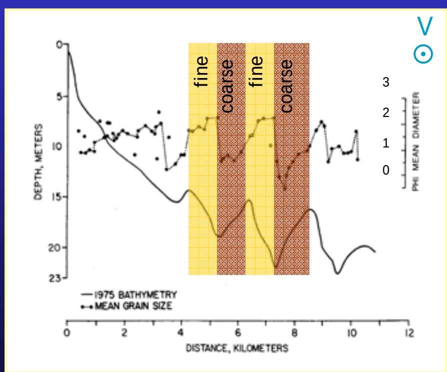
red arrow: direction of storm-driven flow

1. Initial formation
2. Finite-amplitude behavior
3. Response to interventions

Field observations reveal:

persistent variations in mean grain size over sfcr

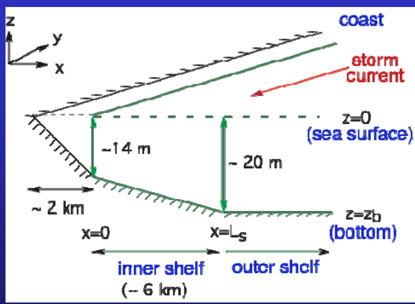
Profile of water depth and mean grain size



finest sediment (largest phi) seaward of the crests

Initial formation and physical mechanism

Trowbridge (1995): sfcr can form as free morphodynamic instabilities in a coupled water - bottom system:



geometry

- Water motion: depth-averaged shallow water equations
- Sediment transport: stirring by waves, transport by currents

  i.e., bedload formulation $\vec{q} = K\,\vec{u}$
- Instability ~ transverse bottom slope of the shelf

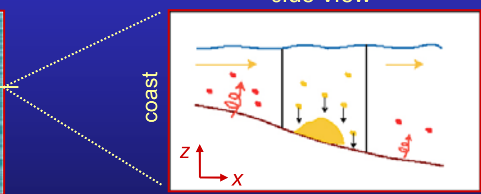
Instability mechanism

~ transverse bottom slope

top view

offshore deflection
of current over a ridge

side view



flow convergence +
non-uniform wave stirring

Formulation of the model

Initial bottom

1. waves → 2. currents

3. sediment transport (mixture)

4. bottom change

dynamics only during storms (5%)

Wave model

- Dispersion relation
- Conservation of wave crests
- Generalized Snell law
- Energy balance
- Dissipation: bottom friction

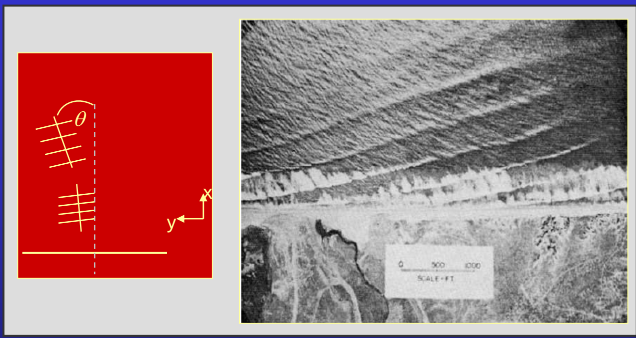
$$\sigma^2 = g\kappa \tanh(\kappa D)$$
$$\frac{\partial \vec{\kappa}}{\partial t} + \vec{\nabla}\sigma = 0$$
$$\frac{\partial k}{\partial y} = \frac{\partial l}{\partial x}$$
$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left(\vec{c}_g E\right) = -Diss$$

σ : wave frequency = constant
g: gravity acceleration
$\vec{\kappa}$: wave vector
k: $\kappa\cos\theta$
l : $\kappa\sin\theta$

$\vec{c}_g$: group velocity
E: energy density
Diss: dissipation
D: water depth

$$E = \frac{1}{8}\rho g H_{rms}^{2}$$

Boundary conditions (far offshore): σ + θ + root mean square wave height (H_{rms})



$$\sigma^2 = g\kappa \tanh(\kappa D)$$

$$\frac{\partial \kappa}{\partial t} + \vec{\nabla}\sigma = 0$$

$$\frac{\partial k}{\partial y} = \frac{\partial l}{\partial x}$$

$$\frac{\partial E}{\partial t} + \vec{\nabla}\cdot\left(\vec{c}_g E\right) = -Diss$$

$$E = \frac{1}{8}\rho g H_{rms}{}^2$$

➡ wave orbital velocity $u_w = \dfrac{\sigma H_{rms}}{2\sinh(\kappa D)}$

used to compute

- **bottom stress experienced by current**
- **sediment transport**

Currents

Depth-averaged shallow water equations

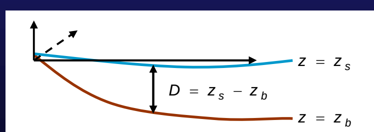
$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v}\cdot\vec{\nabla}\right)\vec{v} + f\,\vec{e}_z \times \vec{v} = -g\,\vec{\nabla} z_s + \frac{\vec{\tau}_s}{\rho D} - \frac{r\,u_w \vec{v}}{\rho D}$$

acceleration | advection | Coriolis | pressure gradient | wind stress | bed shear stress

- **Only storm conditions considered -> linearized bed shear stress**
- **Bottom friction parameter depends on wave orbital velocity**
- **Current is driven by (prescribed) wind stress (tides: not important)**

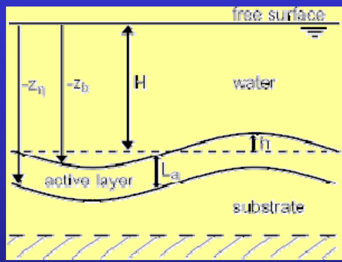
Mass conservation equation

$$\frac{\partial D}{\partial t} + \vec{\nabla}\cdot\left(D\,\vec{v}\right) = 0$$



Sediment mass balance

1 layer model
(no vertical sorting)



For N size fractions:

$$(1-p)\left\{F_i \frac{\partial h}{\partial t} + L_a \frac{\partial F_i}{\partial t}\right\} = -\vec{\nabla}\cdot\langle\vec{q}_i\rangle \ ,$$

$$\sum_{i=1}^{N} F_i = 1 \ .$$

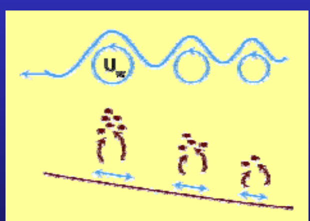
two-size
sand mixture
(sizes d_1 and d_2)

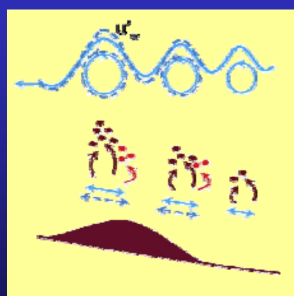
where
- p : bed porosity
- F_i : fraction of sediment with ϕ_i=-log$_2$ d_i (size d_i in mm)

Sediment transport and sorting

- Stirring by waves, transport by storm-driven currents
- Effect of local bedslope

stirring of
sediment by
waves





- Only dynamic hiding
  (fine grains feel less effective shear stress)
- Formulation hiding functions: Day + Garcia/Parker

Sediment transport and sorting

$$\vec{q}_i = F_i \left\{ G_{bi}\vec{q}_b + G_{si}\vec{q}_s \right\} \; ,$$

$$G_{bi} = \left(\frac{d_i}{d_m}\right)^{c_b} \; , \quad G_{si} = \lambda_E^5 \left(\frac{d_i}{d_m}\right)^{c_s} \; , \quad \lambda_E = 1 - c_\sigma \sigma$$

$$\vec{q}_b = Q_b(u_w)\,\vec{v} - \lambda_b(u_w)\,\vec{\nabla} z_b$$

$$\vec{q}_s = Q_s(u_w) D\vec{v} - \lambda_s(u_w)\,\vec{\nabla} z_b$$

advective bedslope

where

- F_i : fraction of sediment with ϕ_i=-log$_2$ d_i (size d_i in mm)
- G_{bi} : hiding function bedload transport (c_b: coefficient)
- G_{si} : hiding function suspended load transport (c_s: coefficient)
- c_σ : coefficient, σ sorting (standard deviation)
- d_m : mean grain size

Stability analysis

$$\begin{array}{lcccc}
u_w & = & U_w(x) & + & \breve{u}_w(x,y,t) \\
\vec{v} & = & (0, V(x)) & + & (u(x,y,t), v(x,y,t)) \\
z_s & = & \zeta(x) & + & \eta(x,y,t) \\
z_b & = & -H(x) & + & h(x,y,t) \\
F_i & = & F_i & + & f_i(x,y,t)
\end{array}$$

basic state **perturbations**

where

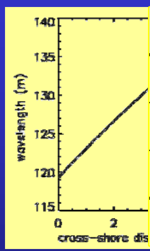
$$U_w \; : \; \text{from wave model}$$

$$f V = g\frac{d\zeta}{dx} \; , \quad \tau_{sy} = r U_w V$$

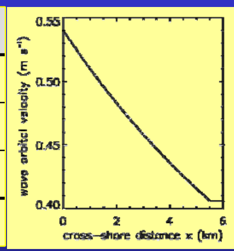
$$F_i = \text{constant}$$

Basic state

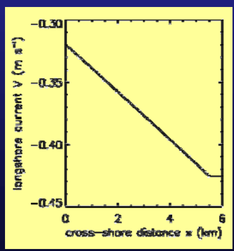
waves



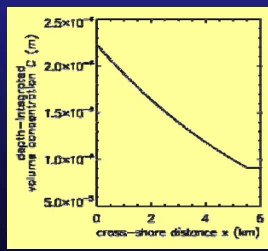
Parameter	Value
T_p	11 s
θ_s	-20° (NE)
$H_{rms,s}$	1.5 m
τ_{sy}	-0.4 N/m² (N)



current



sediment concentration



Linear stability analysis:

Perturbations are small →

$$
\begin{aligned}
u_w &= U_w(x) &&+ e^{\Omega t}\, e^{iky}\, \breve{u}_w(x) \\
\vec{v} &= (0, V(x)) &&+ e^{\Omega t}\, e^{iky}\, (\breve{u}(x), \breve{v}(x)) \\
z_s &= \zeta(x) &&+ e^{\Omega t}\, e^{iky}\, \breve{\eta}(x) \\
z_b &= -H(x) &&+ e^{\Omega t}\, e^{iky}\, \breve{h}(x) \\
F_i &= F_i &&+ e^{\Omega t}\, e^{iky}\, \breve{f}_i(x)
\end{aligned}
$$

=> eigenvalue problem

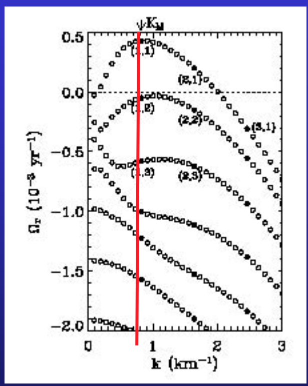
Eigenvalues: growth rate $\Omega_r = \mathrm{Re}(\Omega)$

migration speed $c = -\mathrm{Im}(\Omega)/k$

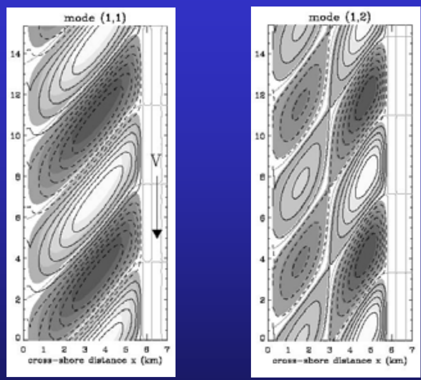
Eigenmodes: $\breve{u}, \breve{v}, \breve{h},$ etc. patterns of perturbations

Results of linear stability analysis

parameter values: Long Island inner shelf



growth rate versus longshore wavenumber



spatial patterns of modes
light colours: crests
solid lines: fine sediment

lengthscale: 7.6 km
timescale: ~1000 yr
migration: 2 m/yr

fine sediment downstream of crest

Nonlinear model

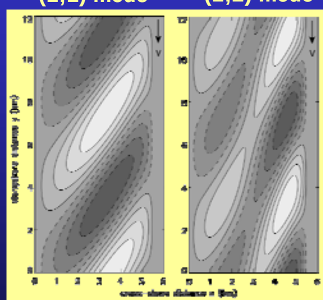
Spectral method: expand perturbations in <u>known</u> eigenmodes (including the fastest growing mode)

e.g. for bottom

$$h = \sum_{j,n_j} A_{jn_j}(t)\, h_{jn_j}(x,y)$$

⇓

(1,1) mode (1,2) mode



→ substitute in equations of motion and project onto adjoint modes

→ <u>differential equations for amplitudes</u> A_{jn_j}

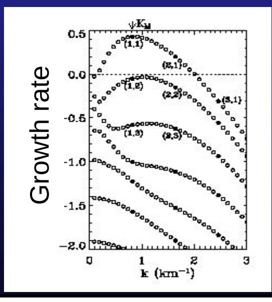
→ truncate after a finite number of eigenmodes

Selection of modes

1. Compute eigenmodes of the linearized system

2. Choose domain with longshore length $L = N \times \lambda_{pref}$ (N integer ≥ 1) with periodic boundary conditions

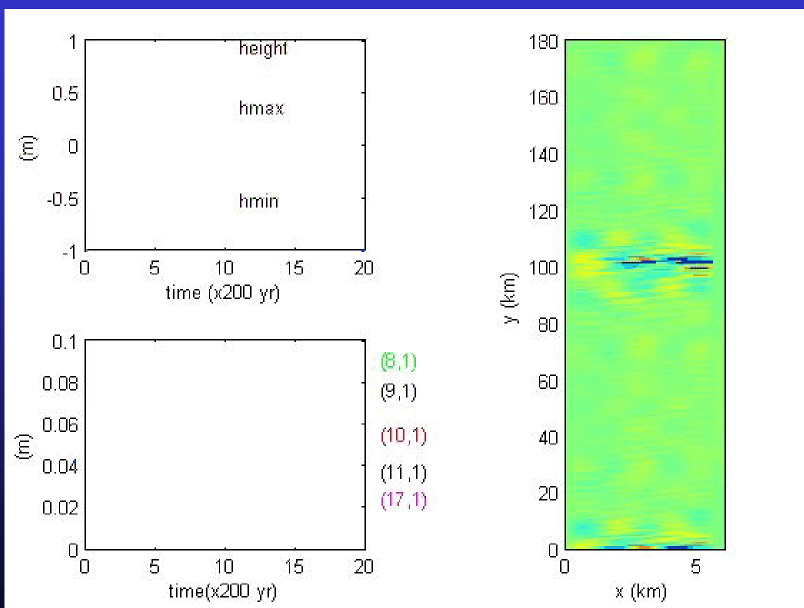
3. Select eigenmodes of linear system (with wavenumbers k) that fit into this domain:
   - subharmonic modes : $k < k_{pref}$
   - the basic mode+superharmonics: $k = j\, k_{pref}$ (j =1,….,J)



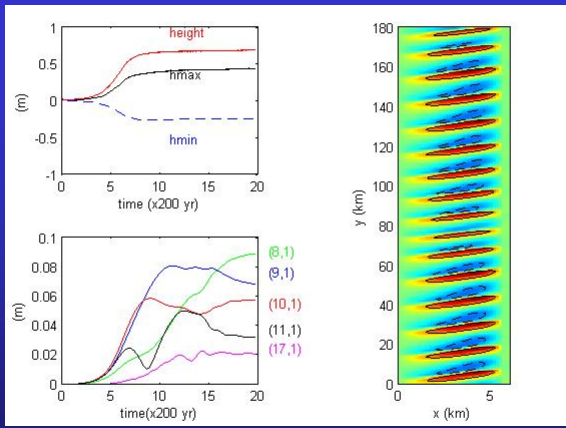
4. For each k: include cross-shore modes with nrs. 1,2,…M_J

Animation of default run (10 subharmonics, J=640, M_J=10:)

time ~ 5% storms; bottom slope is 10% of measured value

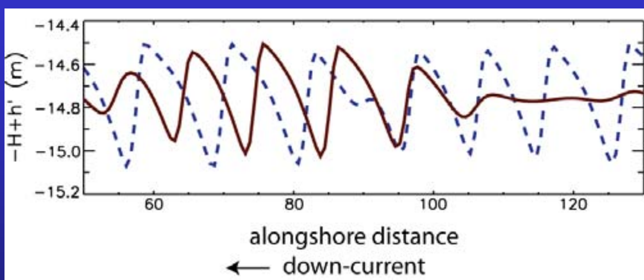


J=640
M_J=10



- ➞ initial exponential growth, followed by **saturation**
- ➞ initially most preferred mode (10,1) not dominant in saturated state; in end state (8,1) has largest amplitude: larger wavelength
- ➞ during transient stage **patch behavior** occurs

Bottom profiles at *x*=5 km at two different times

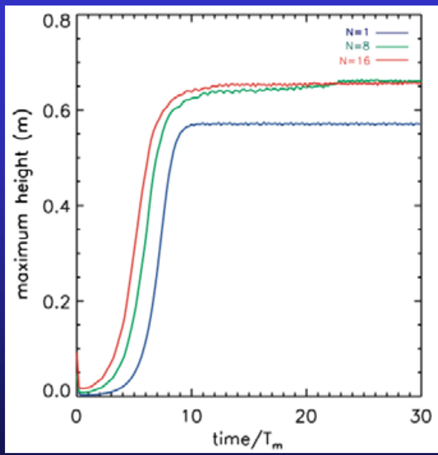


brown: t/T_m=8, blue: t/T_m=20
(for this small β: T_m=100 yr

Note the asymmetric shape: steep fronts

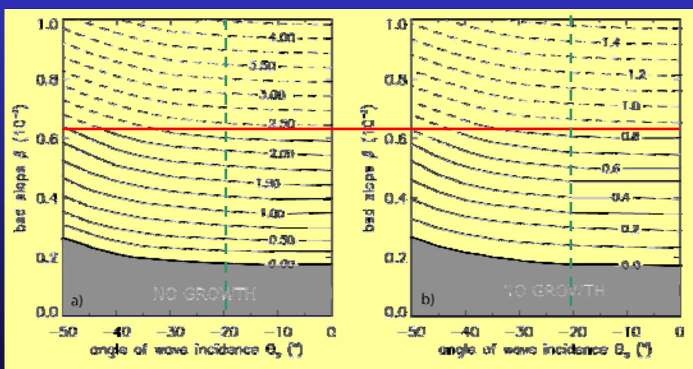
Sensitivity to nr. of subharmonic modes (*N*)

10% of observed bottom slope



- Final height and saturation time **depend** only weakly on *N*
- Bottom patterns at certain time *t* strongly depend on *N*
- If *N*>1: dominant mode in saturated state has longer wavelength than the initially fastest growing mode

Sensitivity to offshore angle of wave incidence



ridge height decreases, saturation time increases with increasing angle of wave incidence

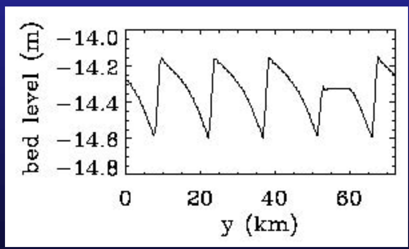
Lines of equal height of ridges (m) in saturated state

Lines of equal reciprocal saturation time (x 10^{-3} yr^{-1})

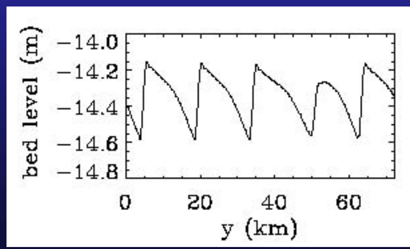
Effect of large-scale interventions on sfcr and stability of the coastal zone

- Start from a fully developed bottom pattern
- Model an intervention and analyse the subsequent response.
- Type of interventions:
  - extract sand from the inner shelf;
  - dump sand on the inner shelf;
  - construct a navigation channel.

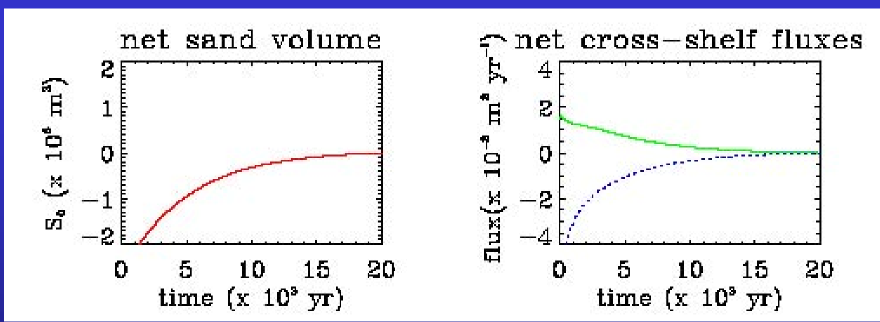
Example: extract sand from a ridge



transect at x=3km, t=0



ibid, after 1000 yr



green: beach → shelf

blue: inner → outer shelf

- sand volume inner shelf restores (timescale ~ 1000 yr)
- significant cross-shelf fluxes
- negative implications for the beach

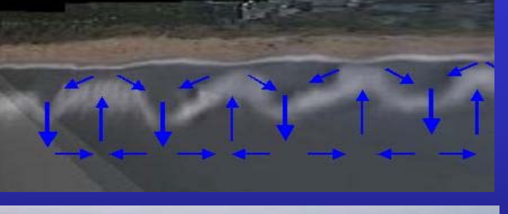
Conclusions (topic A: sfcr)

1. Sfcr can form due to self-organization: transverse slope mechanism
2. Important factors: depth-dependent stirring of sediment by waves, transport by storm-driven flow
3. Sorting of sediment over sfcr can be modeled
4. Nonlinear spectral model-> saturation behavior
   subharmonics results in lengthening of patterns
5. Extraction of sand and dredging of navigation channels have negative implications for the stability of the beach (its sand volume decreases).

Present work:

- finite difference model (larger bottom slopes β)
- effect of sea level changes

Topic B: alongshore rhythmic bars



Crescentic bars and rip channels

Shore-oblique bars

Explanations for the formation of rhythmic bars:

a) They are forced by infragravity edge waves
(Bowen, 1971; Holman and Bowen, 1982)

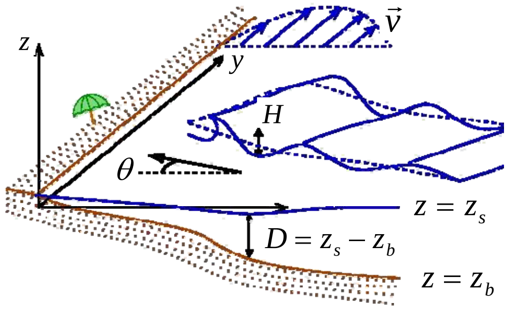
Drawbacks:

- Not obvious how these edge waves are generated (with the necessary phase-locking)
- The possible feedback from the developing morphology into the flow is discarded

b) They emerge by morphodynamic self-organization
(Hino, 1974; Falqués, Coco & Huntley, 2000; ....)

Thus, positive feedbacks occur between certain topographic perturbations and the associated perturbations on the waves and currents.

A mechanism for formation of rhythmic topography and rip currents in the nearshore zone



H : wave height

θ : angle of wave incidence

$\vec{v} \rightarrow$ depth-averaged current

$D = z_s - z_b \rightarrow$ water depth

$z_b \rightarrow$ bed level

Waves approaching the coast break and cause

- mean set-up of water level (~ 1 m)
- longshore currents (~ 1 m/s)

Equations of motion:

mass
$$\frac{\partial D}{\partial t} + \frac{\partial}{\partial x_j}(D v_j) = 0$$

momentum
$$\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = -g \frac{\partial z_s}{\partial x_i} - \frac{1}{\rho D}\frac{\partial}{\partial x_j}(S'_{ij} - S''_{ij}) + \frac{\tau_{b\,i}}{\rho D} \quad , \quad i = 1,2$$

Depth-averaged equations for currents

Waves affect currents via

- radiation stresses S_{ij}
- turbulent stresses S'_{ij} (mixing depends on wave breaking)
- bed shear stress (components τ_{bi})

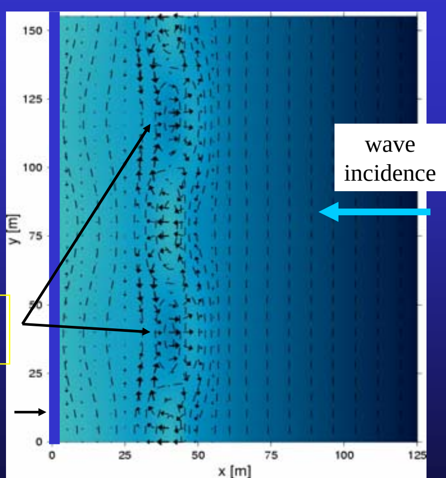
=> Add equations for waves (phase-averaged equations)
They govern frequency ω, wave vector and energy density)

=> Add equation for bed level

Crescentic bars: linear stability analysis

(Calvete *et al.*, 2005)

- Basic equilibrium topography: linear longshore bar without crescentic pattern
- Can be unstable with respect to growing perturbations in the topography and the flow



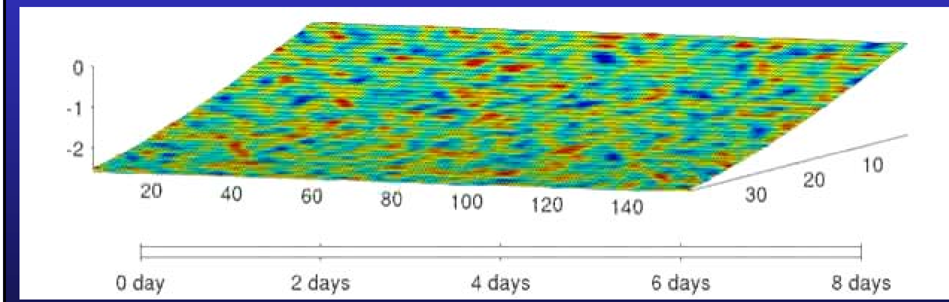
Rip currents and rip channels

coastline

Instability occurs only for intermediate beach conditions, between fully dissipative and fully reflective

Also when longshore bar is absent bars will emerge

- initial formation (Falqués *et al.*, 2000)
- long-term evolution using a finite difference model (Caballeria *et al.*, 2002)

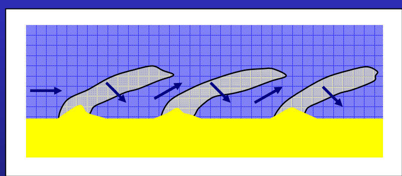


Note the tendency to form larger spacings

Obliquely incident waves

Oblique wave incidence much more complex.
Interaction of:

• 'Bed-surf' effect: Coupling of topography and waves.
• 'Bed-flow' effect: Deflection of the longshore current by the bars. (similar to sfcr)

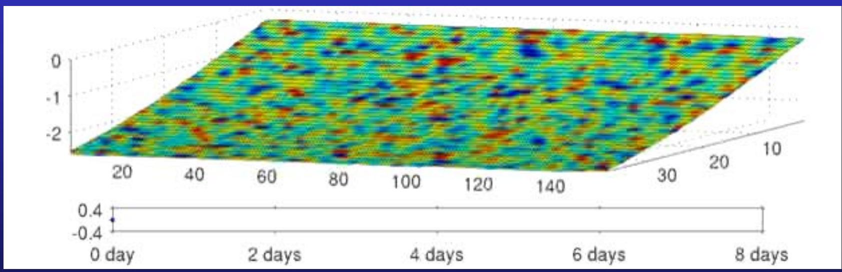


Physical analysis of model reveals that

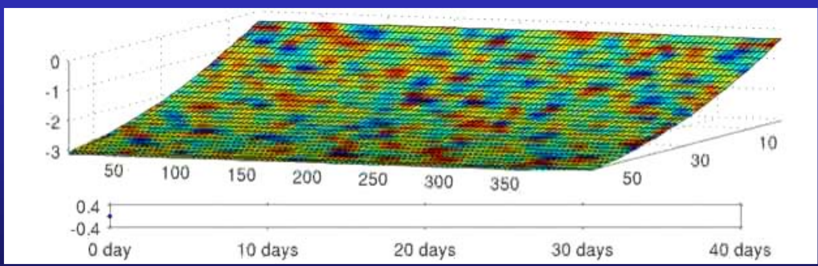
If depth-mean concentration

• decreases in offshore direction: upcurrent bars
• increases in offshore direction: downcurrent bars

Finite-amplitude evolution of down-current bars (Garnier *et al*., 2006)



Finite-amplitude evolution of up-current bars (Garnier *et* al., 2006)



Conclusions (topic B)

1. The equilibrium beach profile can be unstable to alongshore non uniform perturbations.

2. The instabilities take place for intermediate beach conditions

3. A number of different surf zone rhythmic bar systems can emerge from these instabilities :
   - Crescentic bars
   - Shore oblique / transverse bars

4. The physical process leading to the formation of the bars is a positive feedback between topography and hydrodynamics:
   - 'bed-surf' coupling
   - 'bed-flow' coupling in case of oblique wave incidence

Questions/remarks?

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• A. Falqués, G. Coco and D. Huntley, 2000. A mechanism for the generation of wave driven rhythmic patterns in the surf zone. J. Geophys. Res. , 105(C10), 24071-24087.

• M. Caballeria, G. Coco, A. Falqués, D. A. Huntley, 2002. Self-organization mechanisms for the formation of nearshore crescentic and transverse sand bars. J. Fluid Mechanics, vol. 465, 379-410.

•J. Damgaard,, N. Dodd, L. Hall, T. Chesher, 2002. Morphodynamic modelling of rip channel growth. Coastal Eng., 45, 199-221.

• F. Ribas, A. Falqués, A. Montoto, 2003. Nearshore oblique sand bars. J. Geophys. Res., 108 (C4), 3119, doi:10.1029.

• D. Calvete, N. Dodd, A. Falqués, S.M. van Leeuwen, 2005. Morphological development of rip channel systems: Normal and near-normal wave incidence. J. Geophys. Res. 110, C100006, doi: 10.1029/2004JC002803.

• R. Garnier, D. Calvete, A. Falqués, M. Caballeria, 2006. Generation and nonlinear evolution of shore-oblique/transverse sand bars. J. Fluid Mech. 567-327-360.

• R. Garnier, D. Calvete, A. Falqués, N. Dodd, 2008. Modelling the formation and the long-term behavior of rip channel systems from the deformation of a longshore bar. J. Geophys. Res. 113, C07053, doi:10.1029/2007JC004632.