Microalgues, biocarburants et couplage hydrodynamique-biologie

J. Sainte-Marie (ANGE)

- BIOCORE (O. Bernard)
- DYLISS (A. Siegel)
- BAMBOO, IBIS, MODEMIC + LOV, IFREMER
- NASKÉO (B. Sialve), ...

➺ A.-C. Boulanger, M.-O. Bristeau, R. Hamouda, B. Perthame

Journées scientifiques - 06/2013 - Rennes

http://mpt2013.fr/

Sustainable/renewable energies

Two aspects

- Algae culture - hydrodynamics-biology coupling
- Marine energies

IEED (Institute of Excellence in Carbon-free Energy)

- GreenStars & Inria Project Lab "Algae in silico"
- France Energies Marines

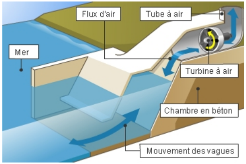
Common features

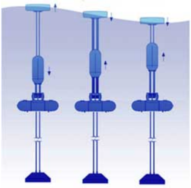
- Strong political/economical supports
- Many small/young companies
- Scientific challenges : modeling, num. anal. & simulations
- Optimization problems ($\neq$ network, $\neq$ intermittence)
- Sustainable development vs. oil price

Marine energies

Capture the waves energy

- Various tested systems
- Objective : be able to simulate the fluid/structure interaction in order to optimize the system

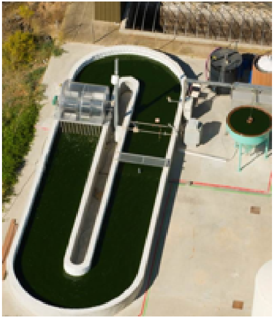




Microalgae can support the 3rd biofuel generation

Description : algae pool driven into motion by a paddle wheel

Companies : EADS, Microphyt, Naskéo, Ondalys, Roquette, Sofiprotéol, Soliance,. . .



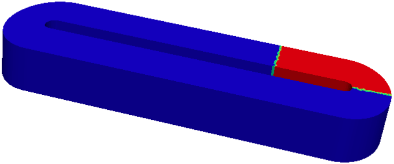
Goal : optimize the biomass production by playing on the nutrients supply, water depth, agitation,. . .

Production : lipids (methanisation), CH_4

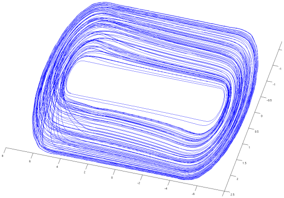
Initial supports : ARC “Nautilus” - PEPS CNRS

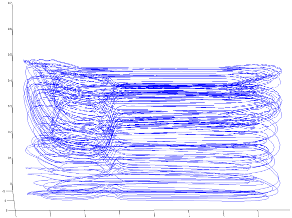
Illustration

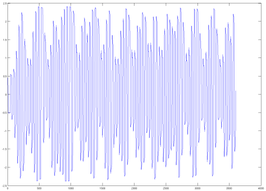
- Algotron (INRA-LBE)



- **3d motion** (anim)







Modelling, prediction & optim. of μ-algae growth

ANGE, BIOCORE, DYLISS, BAMBOO, IBIS, MODEMIC

- Genomic
  - individual scale
  - reconstruction of metabolic networks
  - reduction to a macroscopic scale
  - lipid & glucid storage
- Macroscopic
  - μ-algae and their dynamical environment
  - light induced adaptation mecanisms
- Hydrodynamics
  - hydrodynamics-biology coupling
  - evaluation of culture strategies

Fluid mechanics + biology

- Navier-Stokes with free surface

$$\begin{cases} \operatorname{div} \underline{\mathbf{u}} = 0, \\ \dot{\underline{\mathbf{u}}} + (\underline{\mathbf{u}}.\nabla)\underline{\mathbf{u}} + \nabla p = \mathbf{G} + \operatorname{div} \underline{\underline{\Sigma}}, \end{cases}$$

- Droop model (Droop 1983)

$$\begin{cases} \frac{dC_1}{dt} = \mu(\frac{C_2}{C_1}, I)C_1 - RC_1 \\ \frac{dC_2}{dt} = \lambda(C_3, \frac{C_2}{C_1})C_1 - RC_2 \frac{dC_3}{dt} = -\lambda(C_3, \frac{C_2}{C_1})C_1 \end{cases}$$

with C_1 : phytoplanktonic carbon, C_2 residual nitrates and C_3 phytoplanktonic nitrogen, I light, R death rate

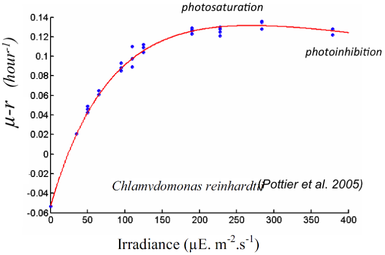
- Advection, reaction and diffusion PDE's

$$\frac{\partial X}{\partial t} + \nabla.(\underline{\mathbf{u}}X) = F(X) + \nu\Delta X$$

with $X = (C_1, C_2, C_3)^T$

Algae : photosynthesis & photoacclimation

- Photosynthesis is well known at steady state in the lab



Growth rate

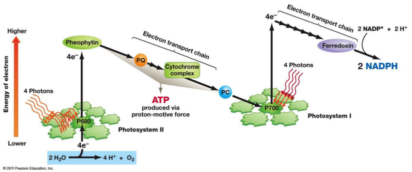
$$\mu(I) = \tilde{\mu}\frac{I}{I + K_s I + \frac{I^2}{K_{i,I}}}$$

Eilers & Peeters (1988)

- Behavior w.r.t. light fluctuations (high frequency) ?

Several time scales

- Slow time scale (1-10 mins)
  - Droop like models (widely used)
- Fast time scale (1-10 secs)



- Many states : rest, storage, busy, restore, dammaged (photoinhibition)

$$X\left(\frac{1}{T}\int_0^T I(t)dt\right) \neq \frac{1}{T}\int_0^T X(I(t))dt$$

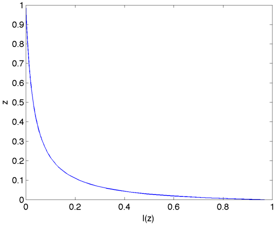
- Sunshine variations, circadian rhythm

Increase light variations

- Light attenuation

$$I(z) = I_0 e^{-\psi(C_2, z)}$$

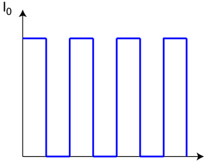
$(C_2$ chlorophyll, biomass)

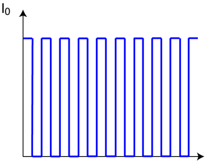


- Light variations

$$\frac{dI_0}{dt} \nearrow \quad \Rightarrow \quad P_{biomass} \nearrow$$

(experiments+models)

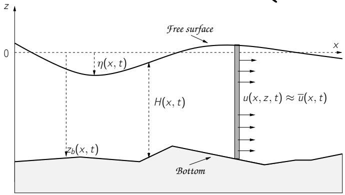




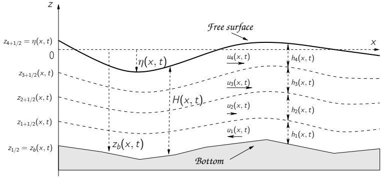
➜ Increase mixing (paddlewheel) ⇒ hydrodynamics-biology coupling

Incompressible Euler (NS) system

$$\left\{\begin{array}{l} \dfrac{\partial u}{\partial x} + \dfrac{\partial w}{\partial z} = 0 \\ \dfrac{\partial u}{\partial t} + \dfrac{\partial u^2}{\partial x} + \dfrac{\partial uw}{\partial z} + \dfrac{\partial p}{\partial x} = 0 \\ \qquad\quad \dfrac{\partial p}{\partial z} = -g \end{array}\right.$$



$\Rightarrow$



- Beyond the Saint-Venant system
- Many contributions (Audusse, Bouchut, LeVeque, Pares, . . .)
- Isopycnal models / non-miscible fluids / sigma-transform

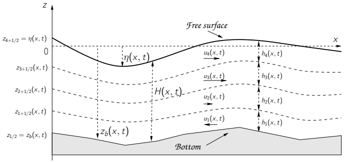
Key idea

Saint-Venant
$u(x,z,t) \approx \bar{u}(x,t)$

$\Rightarrow$

"Multilayer" Saint-Venant
$u(x,z,t) \approx \sum_{\alpha=1}^{N} \mathbf{1}_{z \in L_\alpha(x,t)} u_\alpha(x,t)$

Approximate Euler system (M2AN, JCP 2011)



- Weak form $(\mathbb{P}_0^t)$ of the Euler system $\mathbb{P}_0^t = \left\{\mathbf{1}_{z\in L_\alpha(x,t)},\ 1 \le \alpha \le N\right\}$

$$\left\{\begin{array}{l} \frac{\partial H}{\partial t} + \sum_{\alpha=1}^{N} \frac{\partial}{\partial x}(h_\alpha u_\alpha) = 0 \\ \frac{\partial (h_\alpha u_\alpha)}{\partial t} + \frac{\partial}{\partial x}\left(h_\alpha u_\alpha^2 + \frac{g}{2} h_\alpha f(\{h_j\}_{j\ge\alpha})\right) = F_{\alpha+1/2} - F_{\alpha-1/2} \end{array}\right.$$

- Only one "global" continuity equation, $H = \sum h_\alpha$
- Exchange terms $G_{\alpha+1/2}$, $F_{\alpha+1/2} = u_{\alpha+1/2} G_{\alpha+1/2} + P_{\alpha+1/2}$,
- $G_{\alpha+1/2} = \sum_{j=1}^{\alpha}\left(\frac{\partial h_j}{\partial t} + \frac{\partial}{\partial x}(h_j u_j)\right)$
- If $G_{\alpha+1/2} \equiv 0$ non-miscible fluids, N cont. equations

Properties of the model (hydro only)

- **Hyperbolicity ?**

$$M(X)\dot{X} + A(X)\frac{\partial X}{\partial x} = 0$$

  - hyperbolic for $N = 2$
  - for $N > 2$, "arrow matrices" and interlacing of eigenvalues
  - large family of entropies

- When $N \to \infty$? ($\approx$ 2×2 system)
- Proposition *The functions* $(h_\alpha, u_\alpha, E_\alpha)(t, x)$ *are strong solutions of MSV iff* $\{M_j(x, t, \xi)\}_{j=1}^{N}$ *is solution of*

$$\frac{\partial M_\alpha}{\partial t} + \xi\frac{\partial M_\alpha}{\partial x} - N_{\alpha+1/2} + N_{\alpha-1/2} = Q_\alpha(x, t, \xi)$$

- Discretization using finite volumes
- Robust & efficient numerical scheme
  - positive, well-balanced, discrete entropy inequality

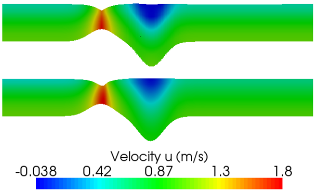
Analytical validation (CMS 2012)

- Analytical solutions to the Euler system
  - 2d and 3d solutions, for any bottom topography $z_b(x, y)$
  - with entropic shocks
  - not necessarily free surface flows
  - In 2d (continuous solutions), u and H characterized by

$$u = \alpha\beta \frac{\cos \beta(z - z_b)}{\sin \beta H}, \qquad \left(g(H + z_b) + \frac{\alpha^2 \beta^2}{2 \sin(\beta H)^2} \right)_x = 0$$

- Recovered by the 2d and 3d codes (also without free surface)

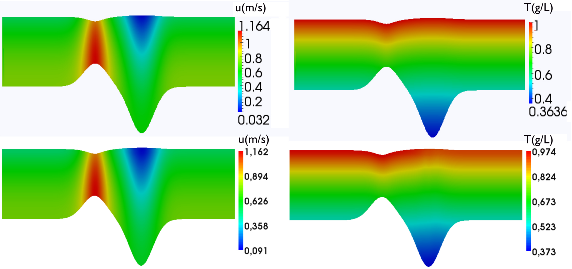
  - analytic
  - simulated



Validation : hydrodynamics + biology

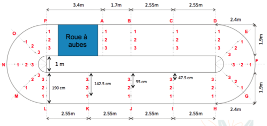
- Analytical validations

(Euler hydro + bio)
$$
\left\{
\begin{array}{l}
\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \\
\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uw}{\partial z} + \frac{\partial p}{\partial x} = 0 \\
\frac{\partial p}{\partial z} = -g \\
\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial wT}{\partial z} = f(x,z)T
\end{array}
\right.
$$



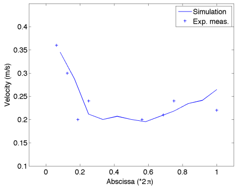
Exp. validations (M2AN 2013)

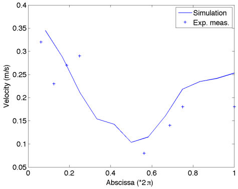
- Measurement points



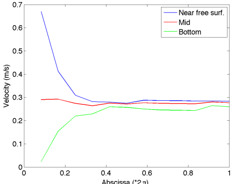
X 3 vitesses X 3 profondeurs X 2 configurations

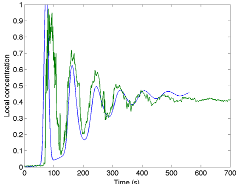
- Comparison (25 Hz, aligned blades, paths 2 & 3, H = 30 cm)





- Comparison (25 Hz, path 2, H = 5, 20, 30 cm) & Tracer





An optimization problem

$$\max P_{algae} \quad vs. \quad \min E_{wheel}$$

Playing on

- Water level
- Paddlewheel (shape, velocity,. . .)
- Nutrients
- Algae species
- . . .

Idea

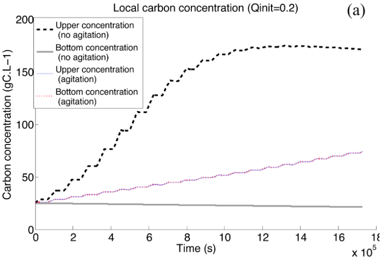
- Many simulations

➾ Optimization (cf. G. Allaire) but for fluid mechanics (e.g. HCLs)

Importance of the paddle wheel

- Algae culture in a raceway
  - 3d Navier-Stokes + Droop model

- Results (PhD A.-C. Boulanger)

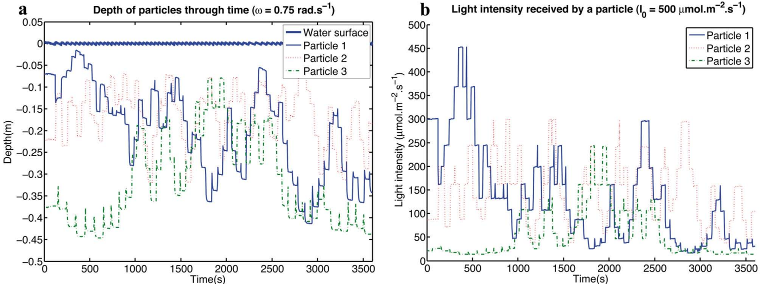


Lagrangian trajectories

- Calculated from hyd. simulations

$$\frac{dM}{dt} = \underline{u}(M(t))$$

- Description : eulerian $\neq$ lagrangian



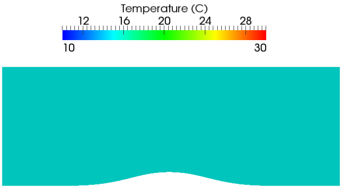
Many degrees of freedom

Experiments

- Many μ-algae species
- Freshwater/marine algae

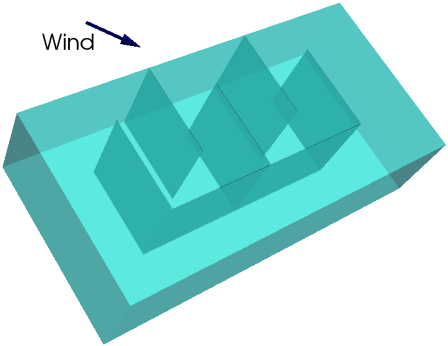
A priori simulations

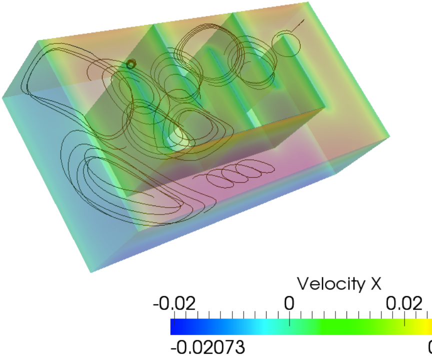
- Raceway with a modified geometry, with obstacles
- Lighting strategies
- Solar driven flows



Salt marshes

- Collaboration with “La compagnie du vent” (GDF-Suez)





Challenges & positioning

4 aspects : modeling, analysis, simulation & experiments

- Genomic
- μ-algae in their environment
- Hydrodynamics-biology coupling
  - incompressible Euler with free surface
  - non-hydrostatic effects & sedimentation

$$\nabla.\underline{\mathbf{u}} = 0$$
$$\partial_t \underline{\mathbf{u}} + (\underline{\mathbf{u}}.\nabla)\underline{\mathbf{u}} + \nabla p = \mathbf{G}$$

- - - - - - - - - -

- Very complex systems
  - many couplings
  - multiscale, with uncertainties
- Goal oriented researches
  - need for scientific breakthroughs, upstream research
  - robust/efficient numerical tools
- From gene to industrial process
  - transfer / complex & changing ecosystem of SME

Capture wave energy

- Collaboration with Openocean
- An experimental device
  (Pecem harbor - Ceara - Brazil)

Obtained results