Numerical modeling of near bottom currents and food particle transport for cold water reef structures

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Outline

- Cold water coral reefs
- Numerical models
- Results for idealized case studies
- Summary

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Cold water coral reefs – *Lophelia Pertusa*

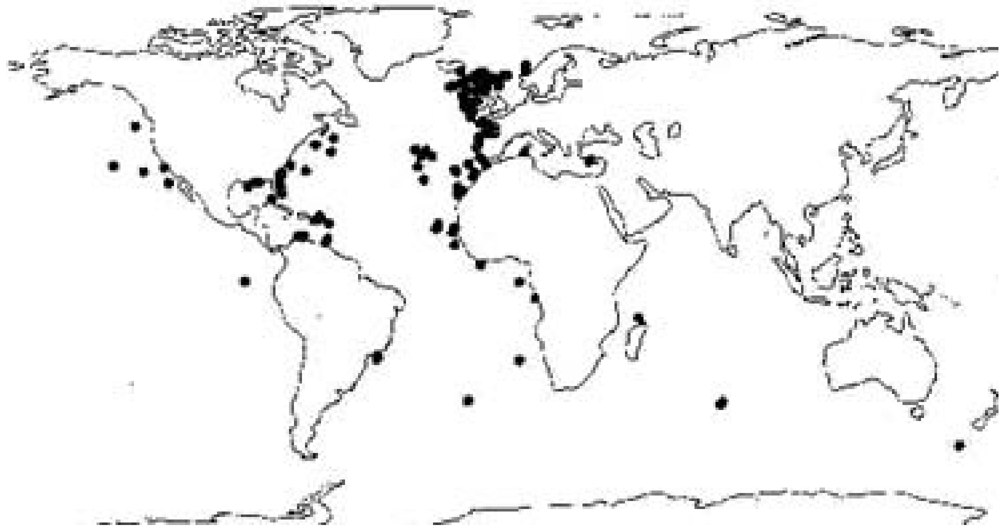
- Reef building, cold water coral

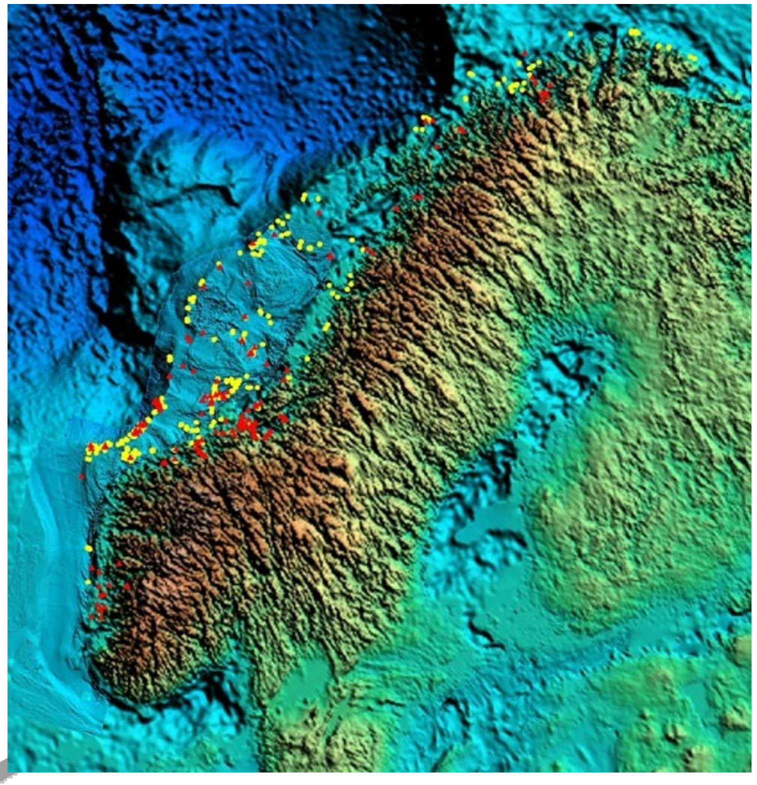
  Global distribution, high concentration in the North Atlantic Ocean.

- Slow growth rate
  - Polyps: ~10 mm/year
  - Reef: ~1 mm/year
- Biodiversity/Habitat:

  Almost 800 species associated with *Lophelia* reefs in North-East Atlantic

- Vulnerability:
  - Bottom trawling
  - Oil/gas exploration, pipelines





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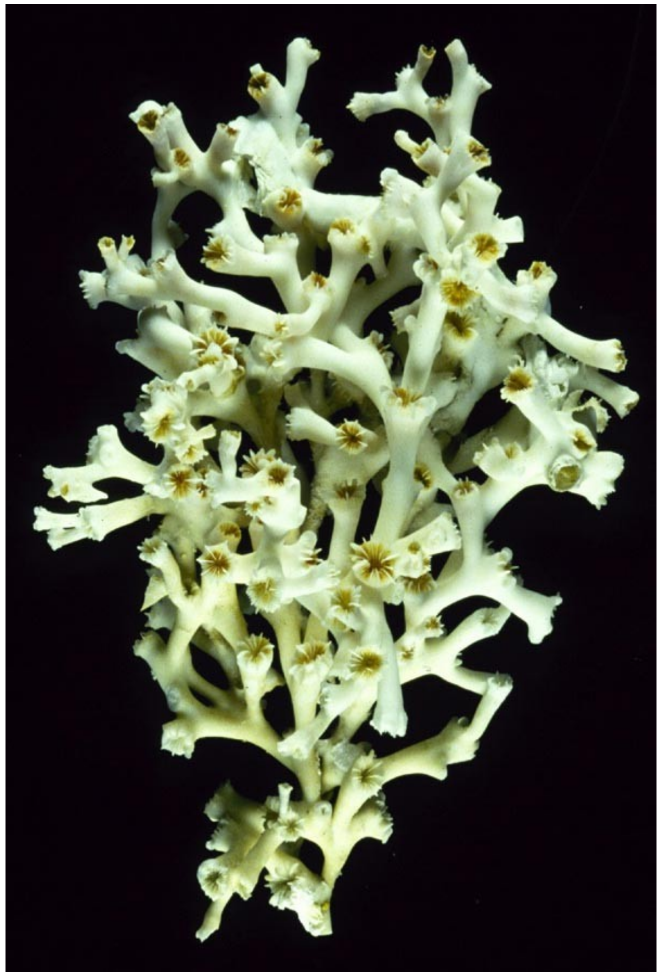
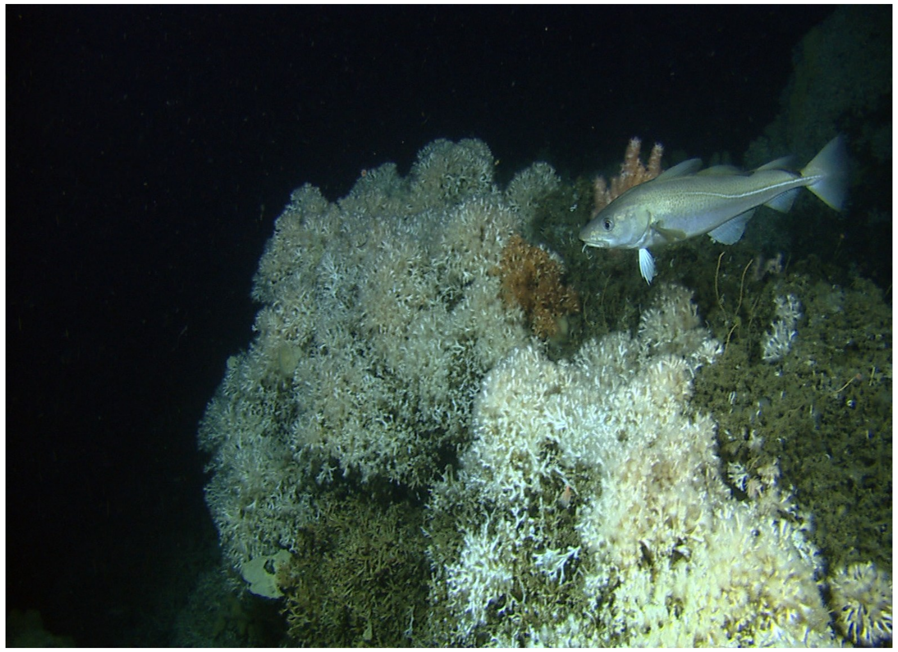
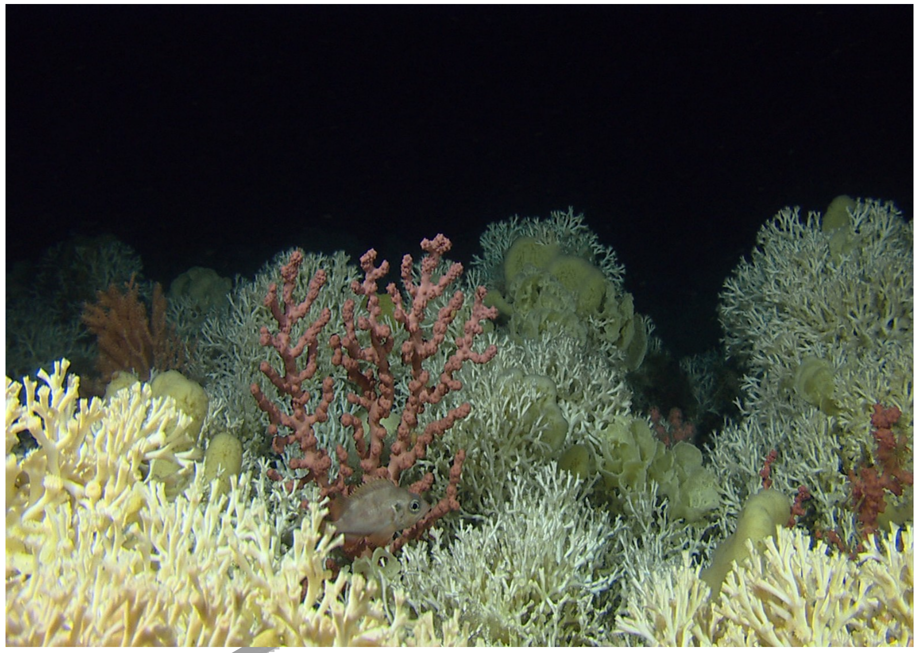
Lophelia Pertusa colonies

- Polyps have diameter of approximately 1 cm
- Branches grow to approximately 4-5 cm before splitting
- Branches can merge, forming a network stabilizing the structure of the colony
- Colonies form 'bushes' with up to 2 m diameter. This size is reached after approximately 300 years.
- Only outer 10 cm of the colony is living corals.







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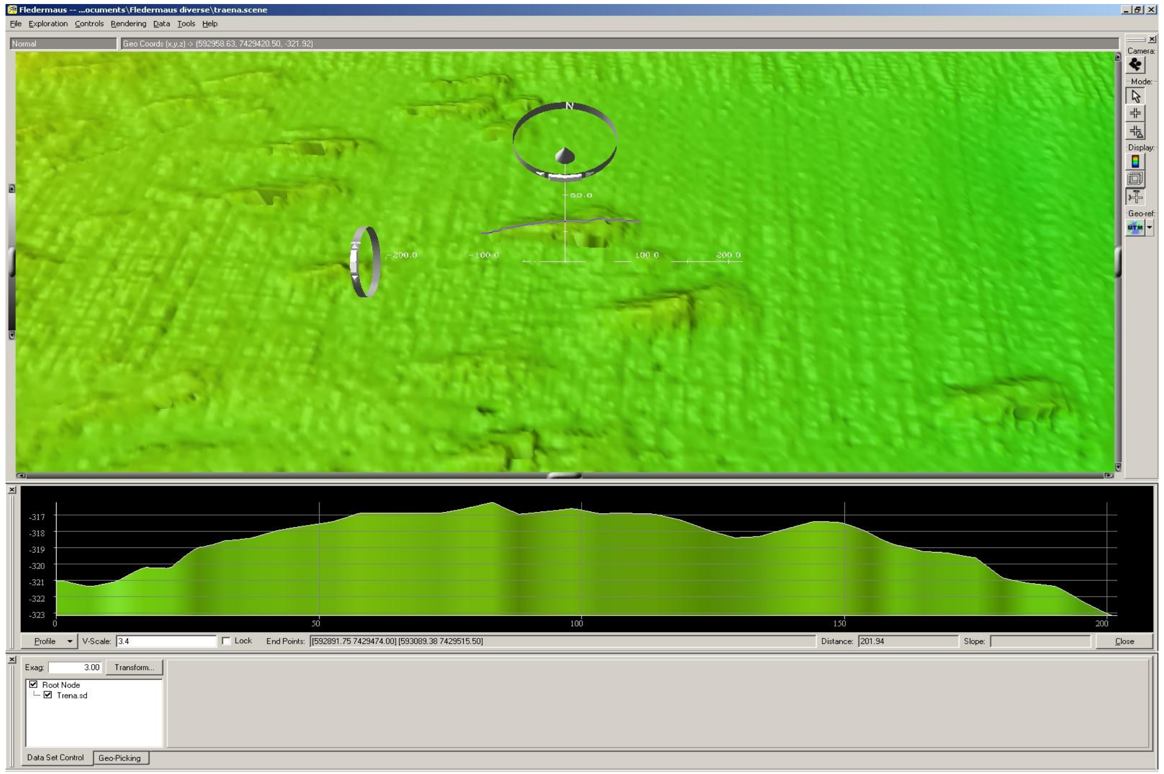
Characteristics of *Lophelia Pertusa* reefs

Reefs at the Træna-deep reef complex

- A 300 km^2 area containing more than 1400 elongated *Lophelia* reefs
- Depth between 250 and 410 m
- Dimensions of typical reef:
  - Length: 150 m
  - Width: 40 m
  - Height: 5-10 m
- Orientation along main current
  - living corals facing direction of current
  - “tail” of dead corals and coral rubble



Reef structure varies between locations.

- Reef heights up to 45 m have been recorded.
- Reefs tend to have conical shapes in locations without dominating current directions

Two theories for *Lophelia* reef settlement and growth

- Settlement determined by favorable current conditions. Nutrients mainly transported with the currents.
- Settlement related to locations with seepage of light hydrocarbons (mainly methane) or nutrient-rich groundwater.

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Important parameters for cold-water reefs and modeling of food particles

Physical parameters that influence cold-water coral settlement and growth

- **Water temperature:** Most *Lophelia* reefs found in water with temperature of 4°C to 8°C. Up to 13°C have been recorded at reef in Mediterranean Sea.
- **Current speed:** Corals rely on currents for transport of food, but strong currents reduce food capturing ability of polyps. Optimal range: 0.5 - 1.0 m/s.
- **Hard substrate:** Usually calcareous or volcanic
- **Salinity:** Most *Lophelia* reefs found in water with salinity 32‰ - 35‰.
- **Other parameters:** Water depth; oxygen, carbon and calcium levels; particle density: food particles and contaminants (sediment smothering); stratification?

Parameters for food particle modeling

- **Reef shape:** Height, length, and slope steepness. Developed reefs typically have slopes with max. steepness of 40° - 60°.
- **Bottom roughness:** Usually increased bottom roughness over reef structures compared to surrounding area. Locally decreased bottom velocities.
- **Feeding efficiency:** Colonies are permeable. Coral coverage is non-uniform.
- **Particle dispersion, turbulent diffusion**

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Numerical models

Ocean General Circulation model

Particle tracking model

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Ocean General Circulation Model: The Bergen Ocean Model (BOM)

- Uniform horizontal discretization using regular Arakawa C-grid.
- Vertical discretization using σ-coordinates.
- Discretized with finite differences.
- Predictor-corrector method for time stepping.
- Mode splitting of 2D barotropic and 3D baroclinic modes, allowing larger time steps when solving full 3D equations.
- Home page: http://www.math.uib.no/BOM/

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Particle tracking model

- Lagrangian advection and diffusion model
- Based on the LADIM model developed by Ådlandsvik and Sundby at the Institute of Marine Research

$$x_i^{(n+1)} = x_i^{(n)} + u_i^{(n)}\Delta t + R \cdot \sigma_u^{(n)}\Delta t$$

$x_i^{(n)}$ = position of particle i at time step n

$u_i^{(n)}$ = particle velocity at time step n

R = Stochastic variable with a Gaussian distribution

- Particle tracking model integrated in BOM. Particles advected after each 3D time step.
- Parallelized: Each processor keeps track of particles within its own sub-domain
  - Potential problem with high concentration of particles at specific locations, e.g. seeding from point source

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Results for idealized case studies

Grid resolution

Time stepping and interpolation methods

Current speed and slope steepness

Feeding efficiency

Turbulent diffusion

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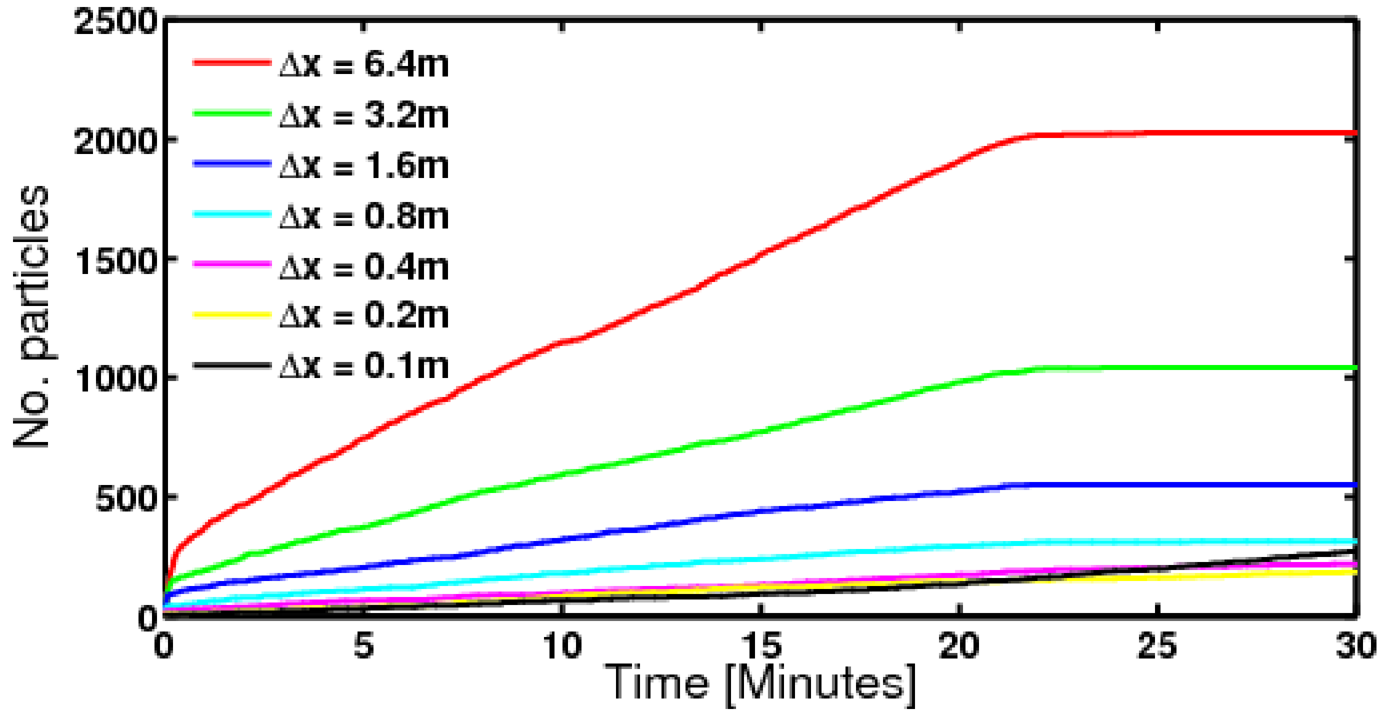
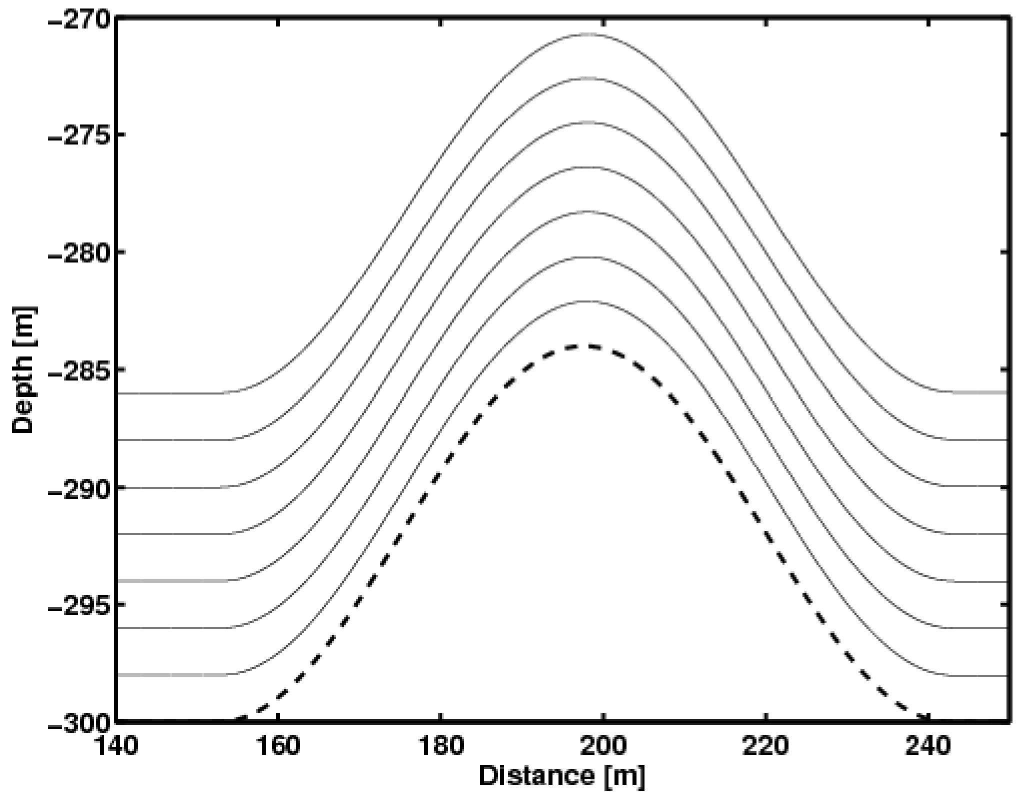
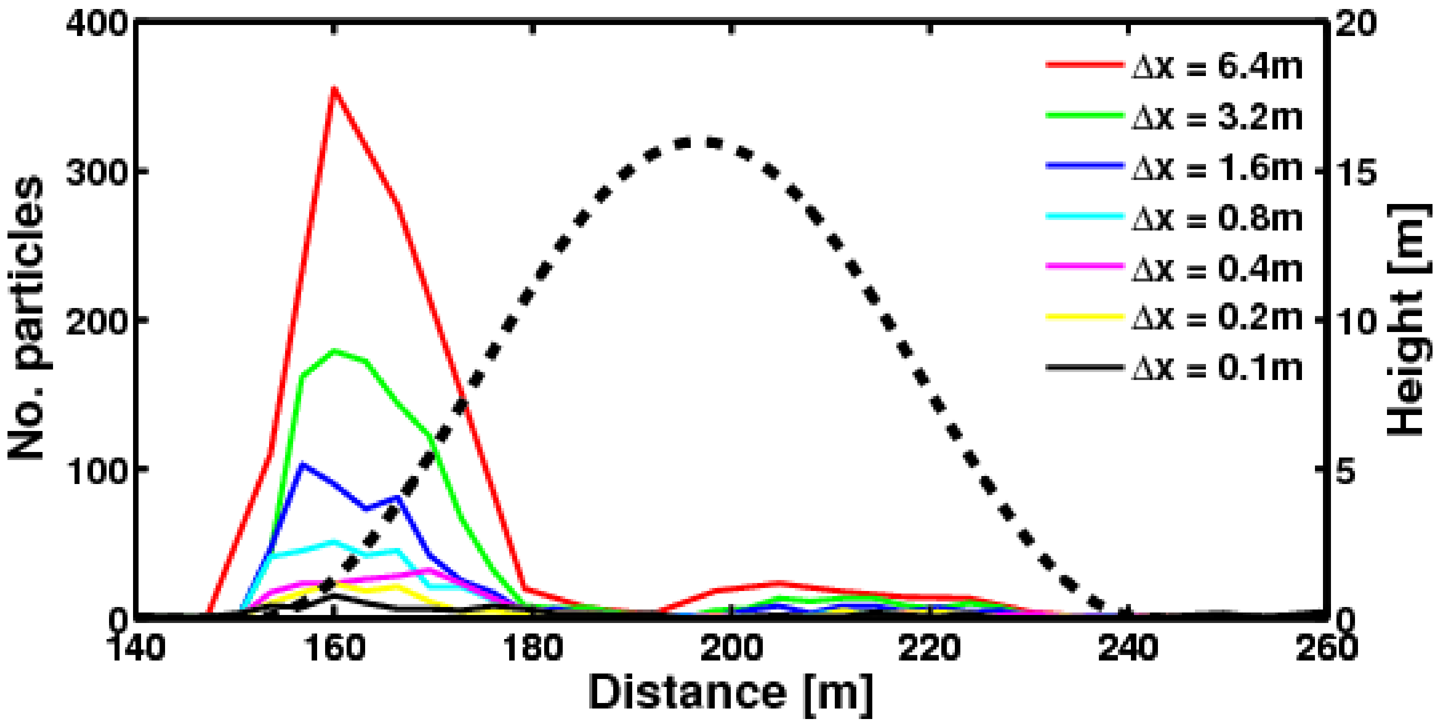
Requirement of high model resolution: Results for 2D ridge simulation

Uniform flow from left to right:
U = 0.25 m/s, 20 000 particles

- Path lines for particles flowing over a ridge
- Accumulated particles in the bottom layer 0.25 m above sea bed
- No random step in tracking model







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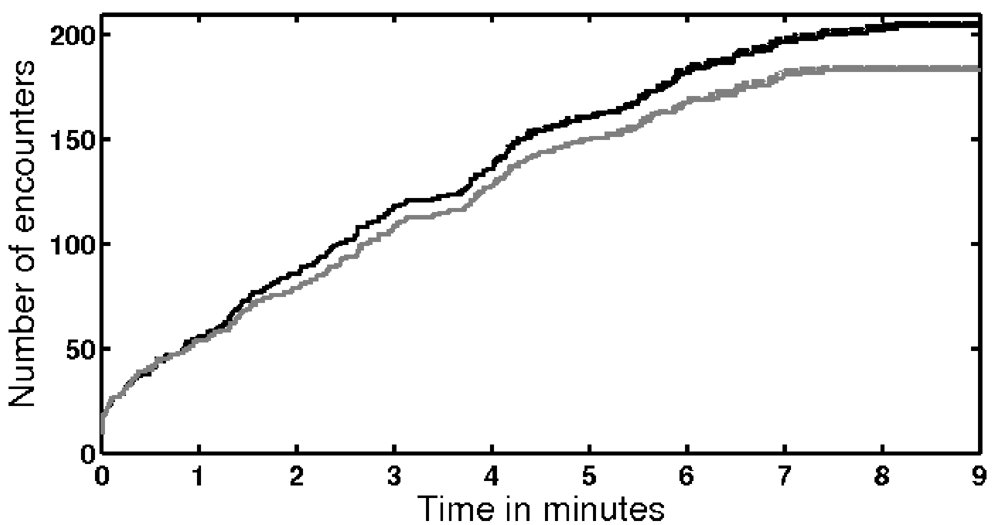
Time stepping methods and interpolation

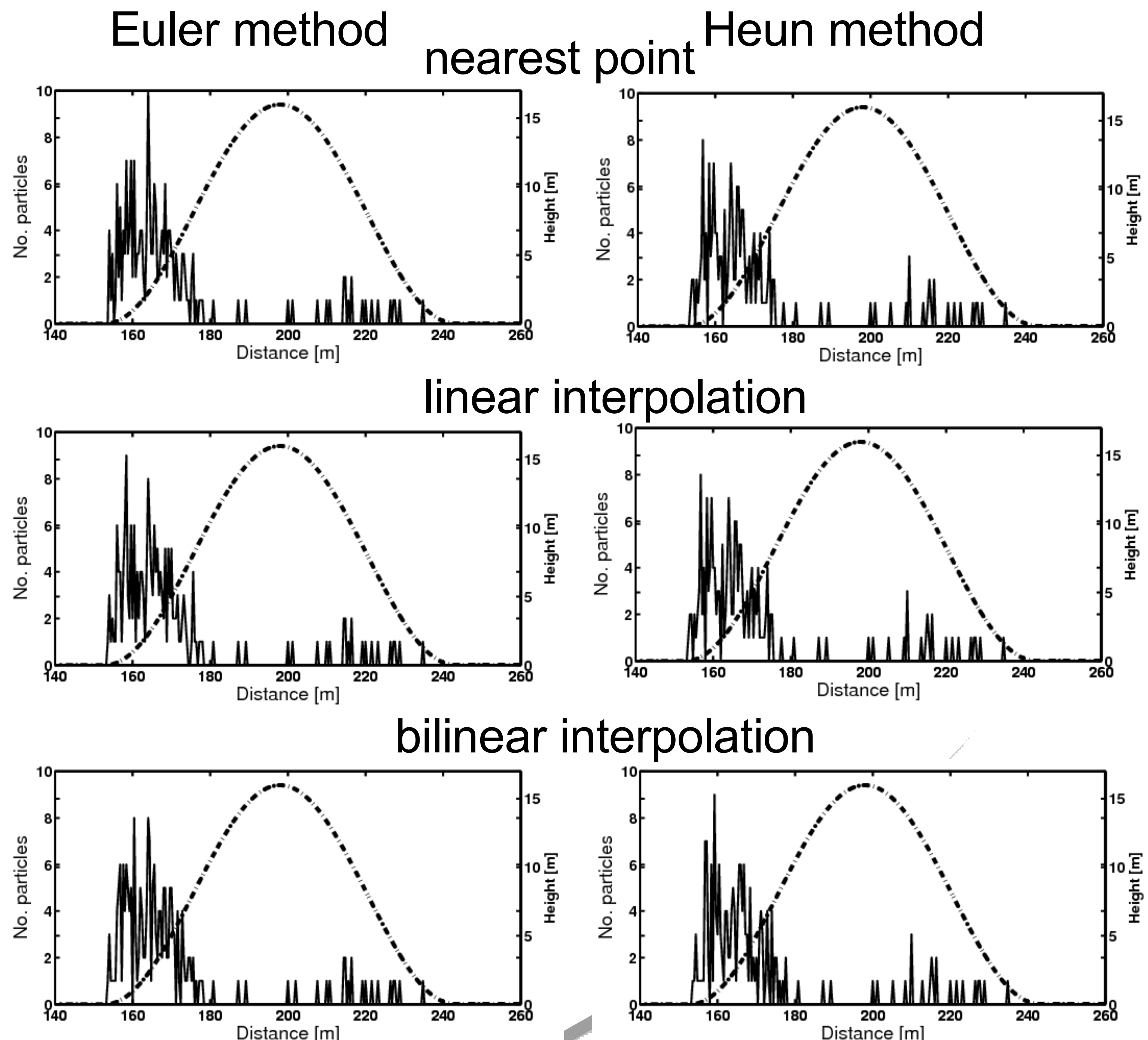
Particle tracking methods

- Time stepping with Euler forward and Heun predictor-corrector methods
- Velocity estimation by nearest point, linear interpolation, and bilinear interpolation
- Benefit of high order methods:
  - No benefit for short time steps
  - Better for long time steps?



Accumulated particle encounters

Black - Euler method; Gray - Heun method



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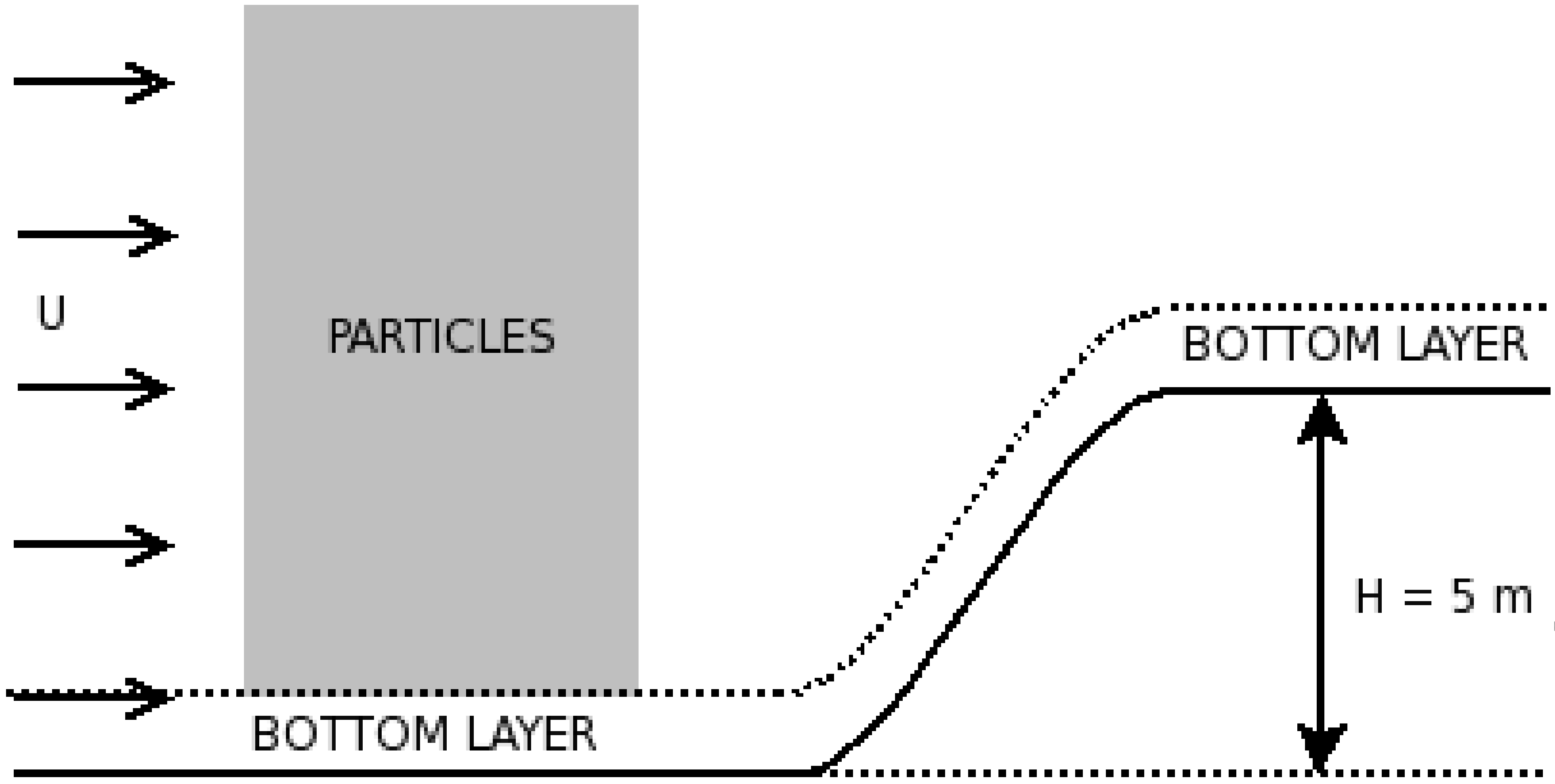
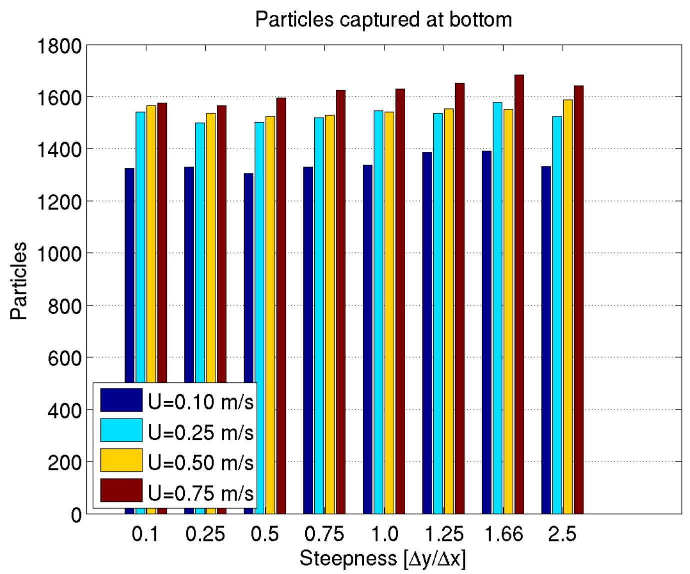
Steady current over sloping topography

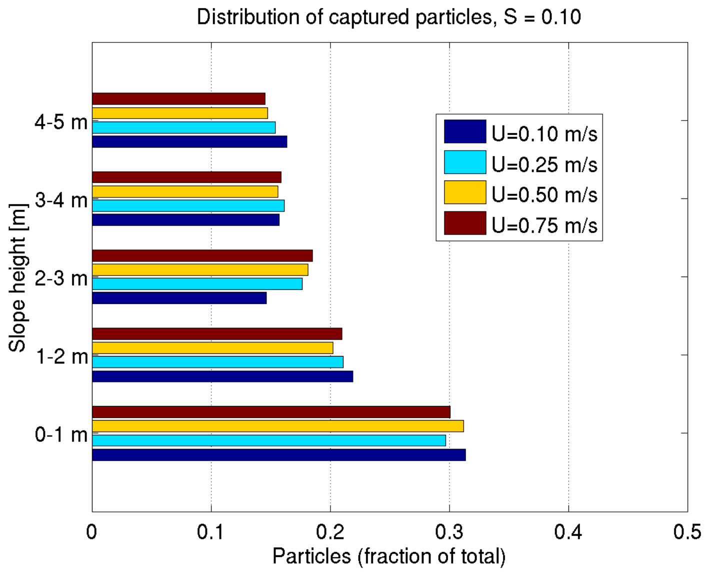
- Current speed and slope steepness
- Feeding efficiency

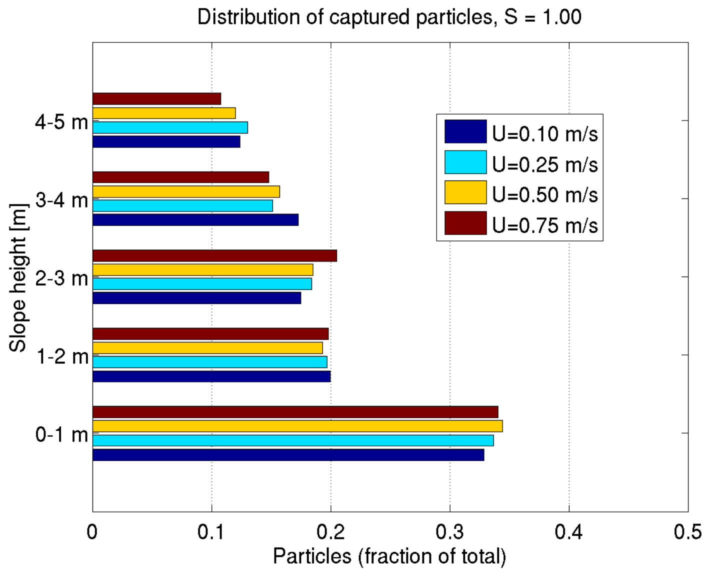


Current speed and slope steepness

- Increased current velocity leads to only slight increase in total number of captured particles
  BUT
  particle distribution is not uniform
- Slope steepness has little impact on total number of captured particles.
- Most particles captured at the bottom of the slope.







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Feeding efficiency and probability of particle capture

Assume corals do not capture 100% of the available particles in the bottom layer.

Simple model for particle capture:

P(particle capture) = feeding efficiency * particle residence time per unit volume

feeding efficiency: number in the range [0,1]

particle residence time: $\min\{ (U_{LAG} * \Delta t) / \Delta x , 1 \}$

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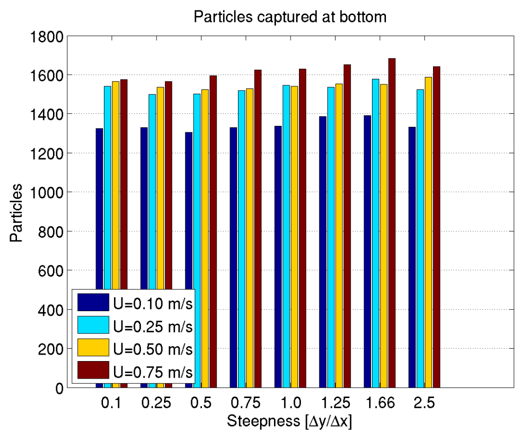
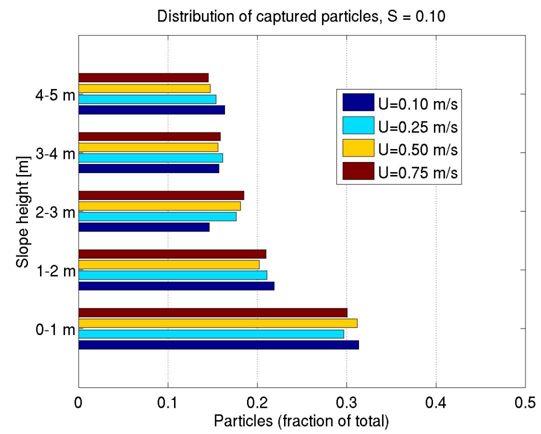
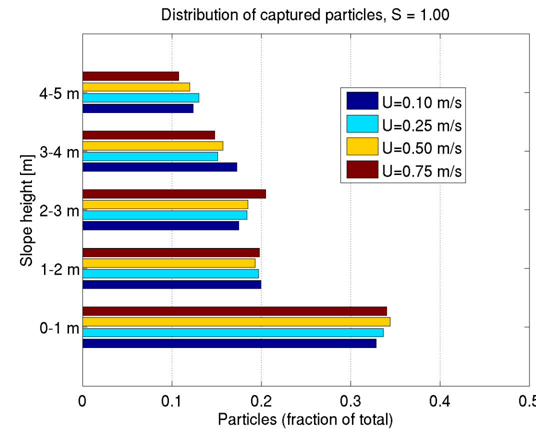
Feeding efficiency | Total number of captured particles | Slope Steepness S = 0.10 | Slope Steepness S = 1.0

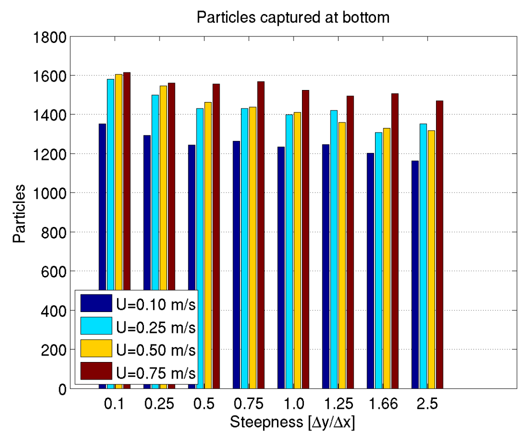
100%

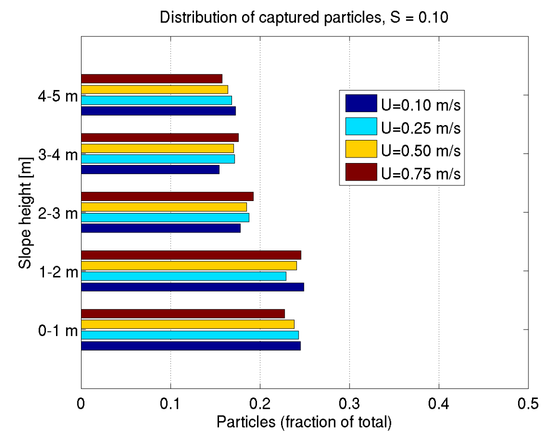


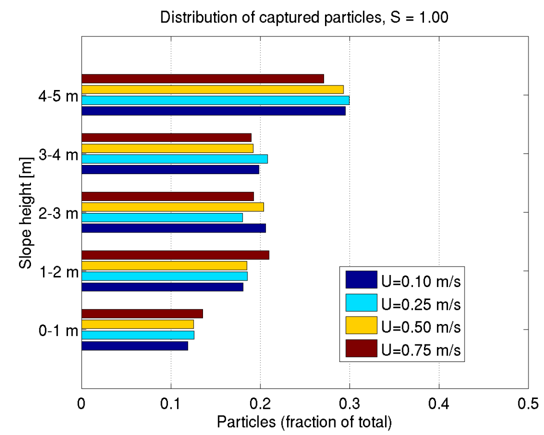




10%







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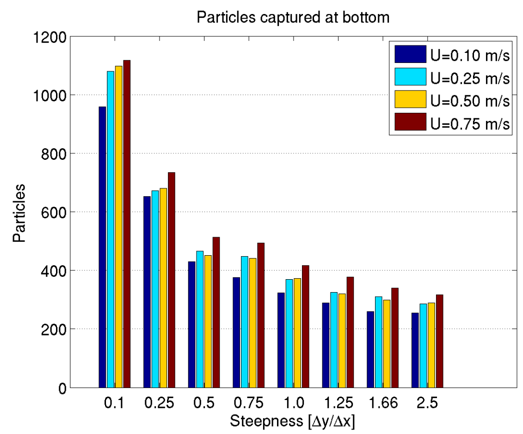

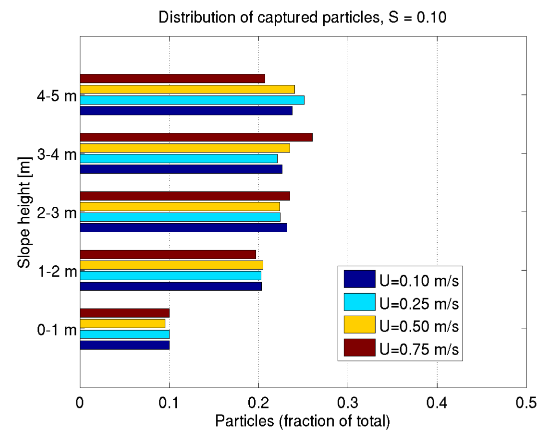

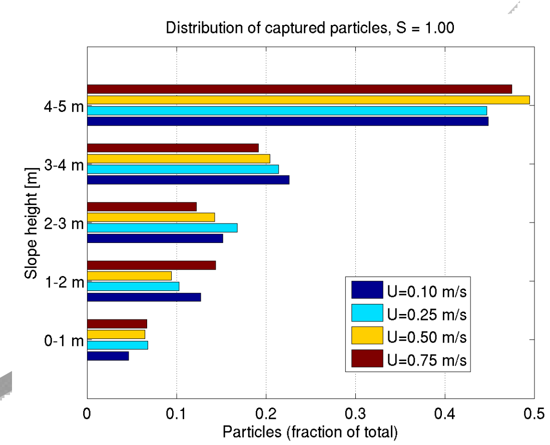

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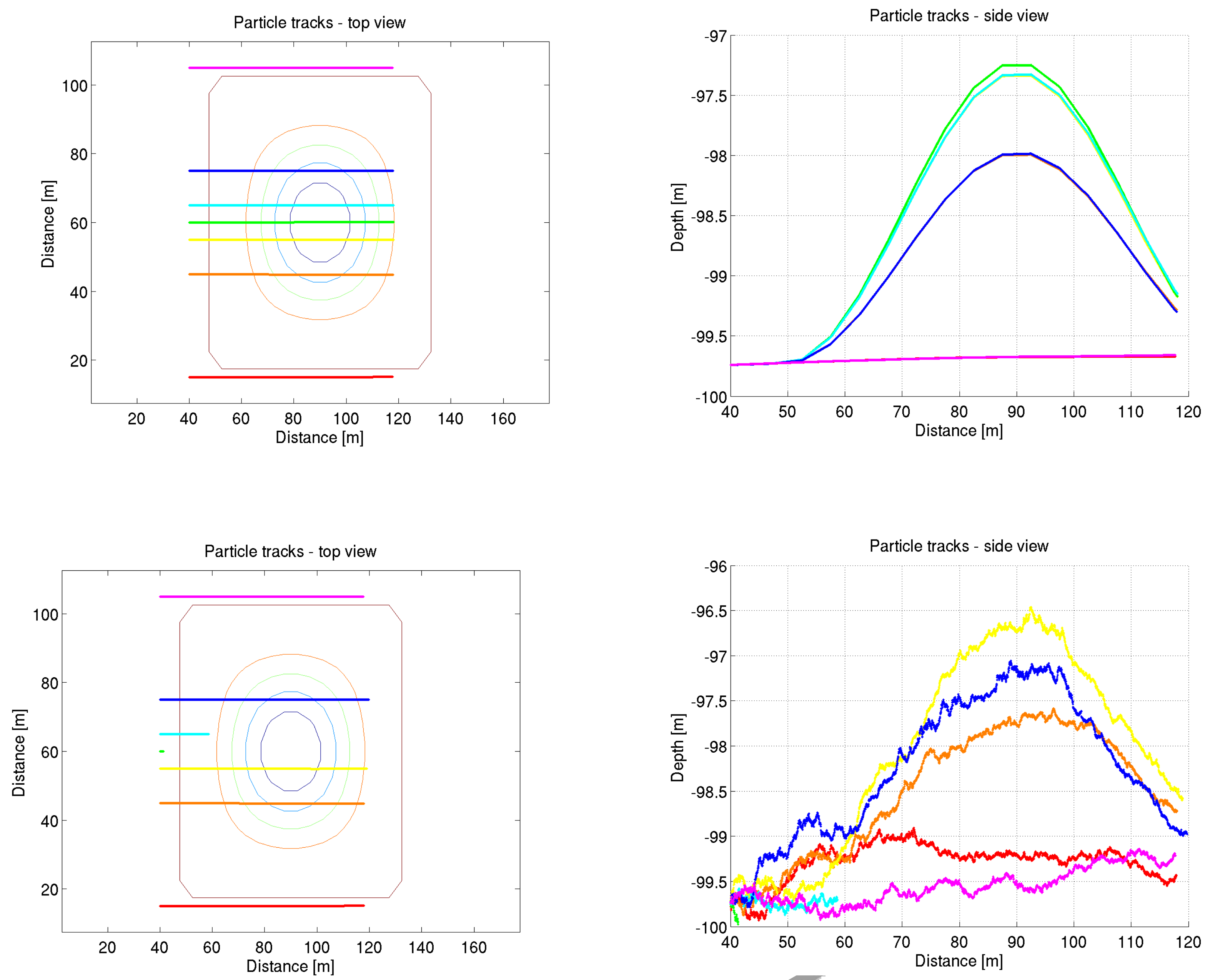
Diffusive vs. non-diffusive modeling

Turbulent diffusion modeling increases probability of moving particles to the bottom layer

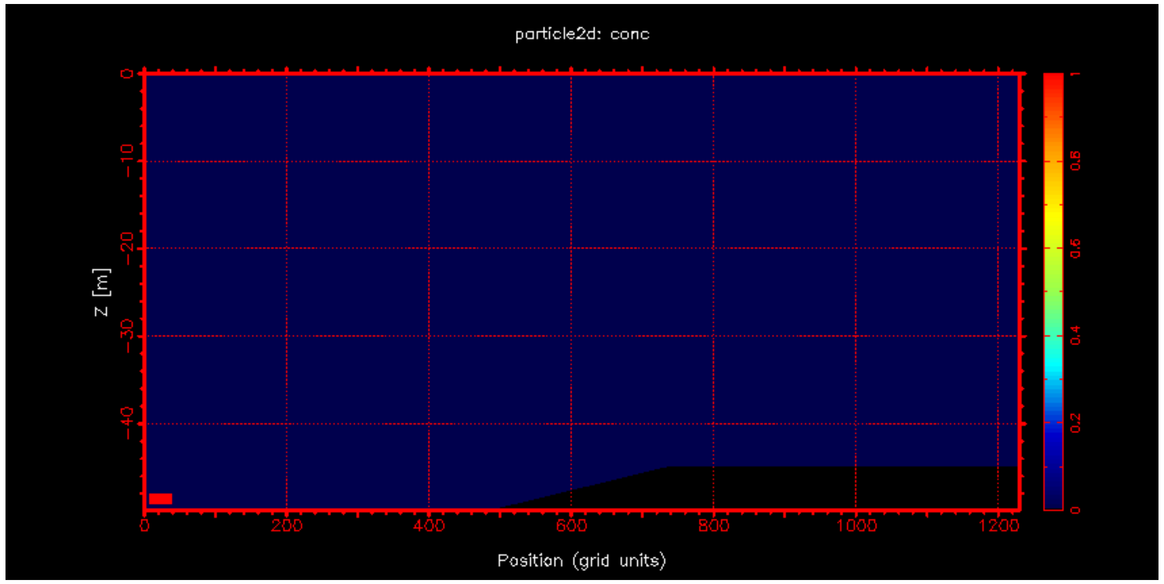
Problem:
What is the right level of diffusion for high resolution modeling?



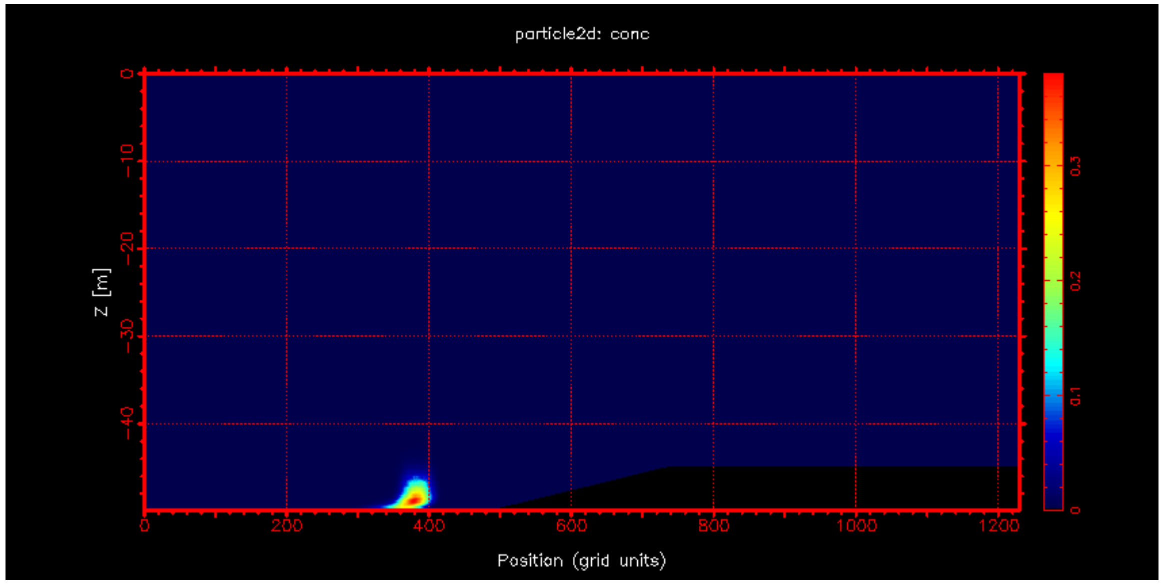
Diffusion of passive tracer

Velocity U = 0.5 m/s; Steepness S = 0.1

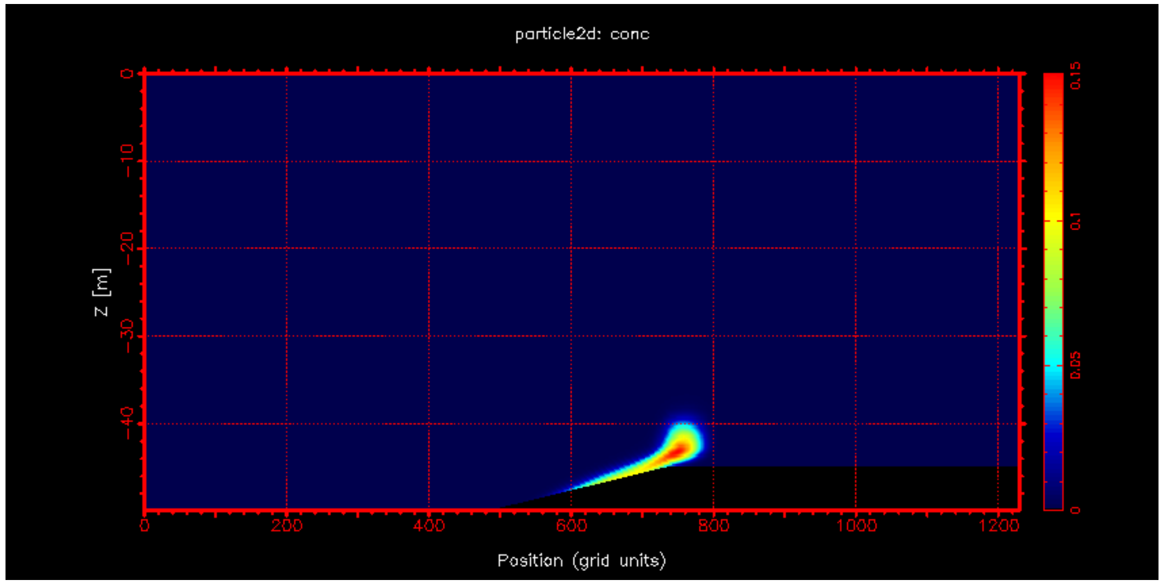
T = 0 s



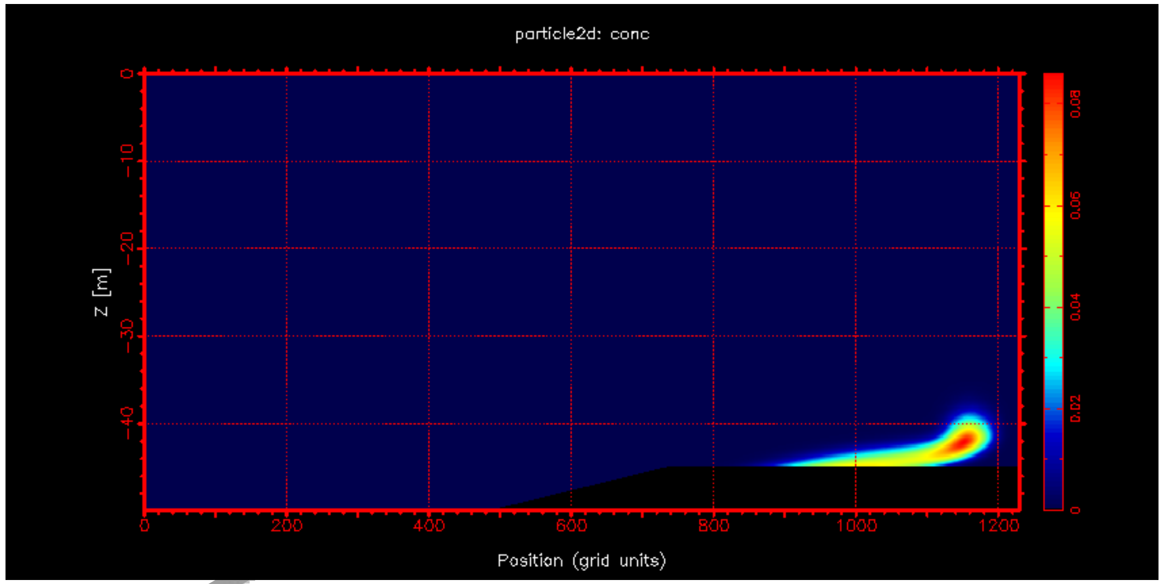
T = 144 s



T = 288 s

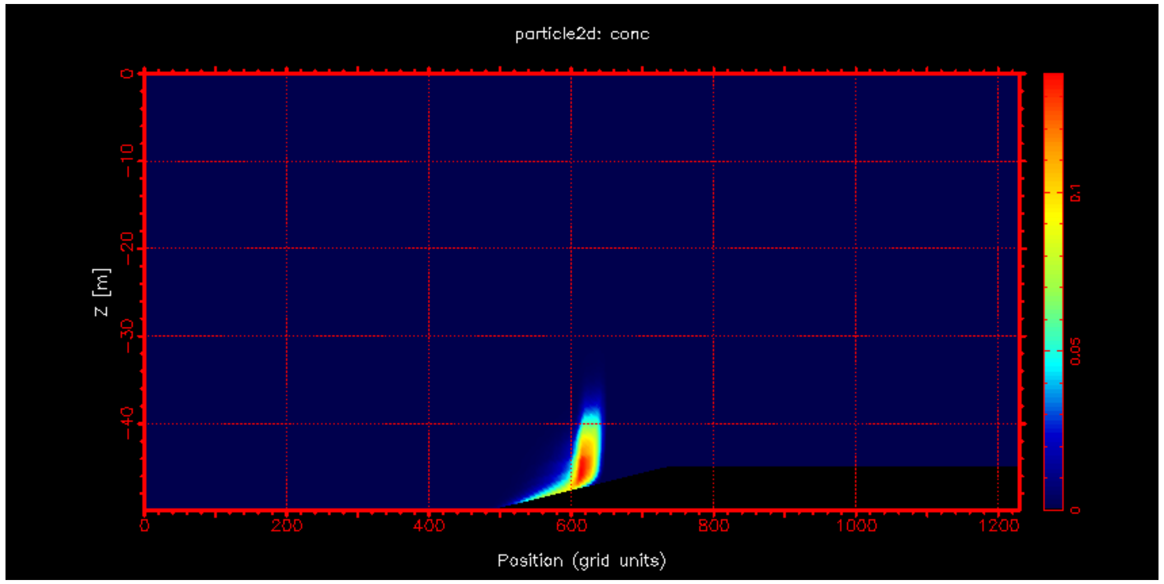


T = 432 s

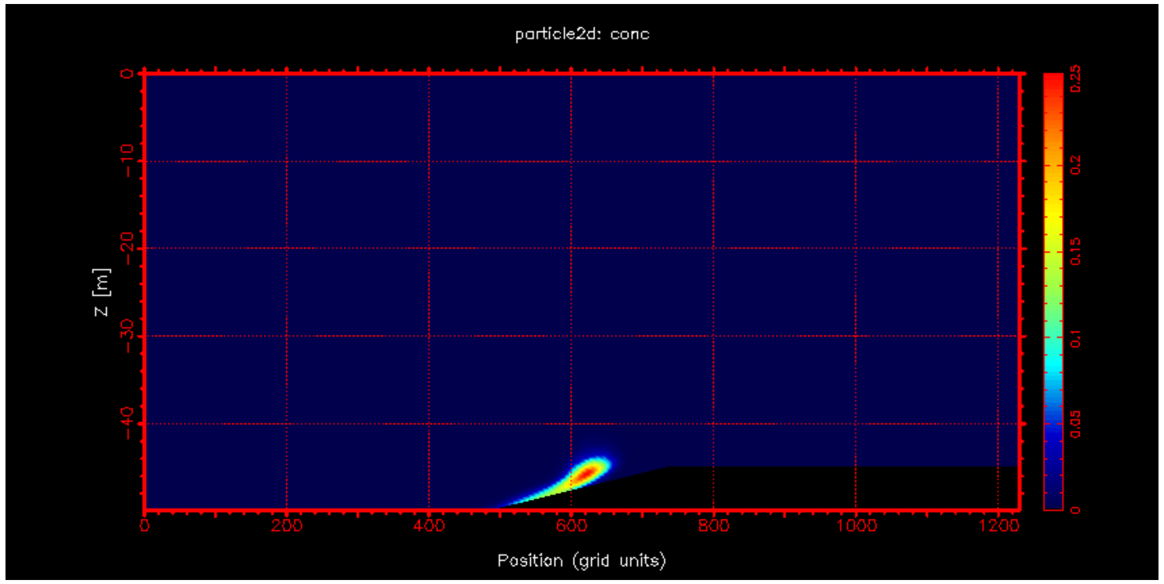


Diffusion of passive tracer

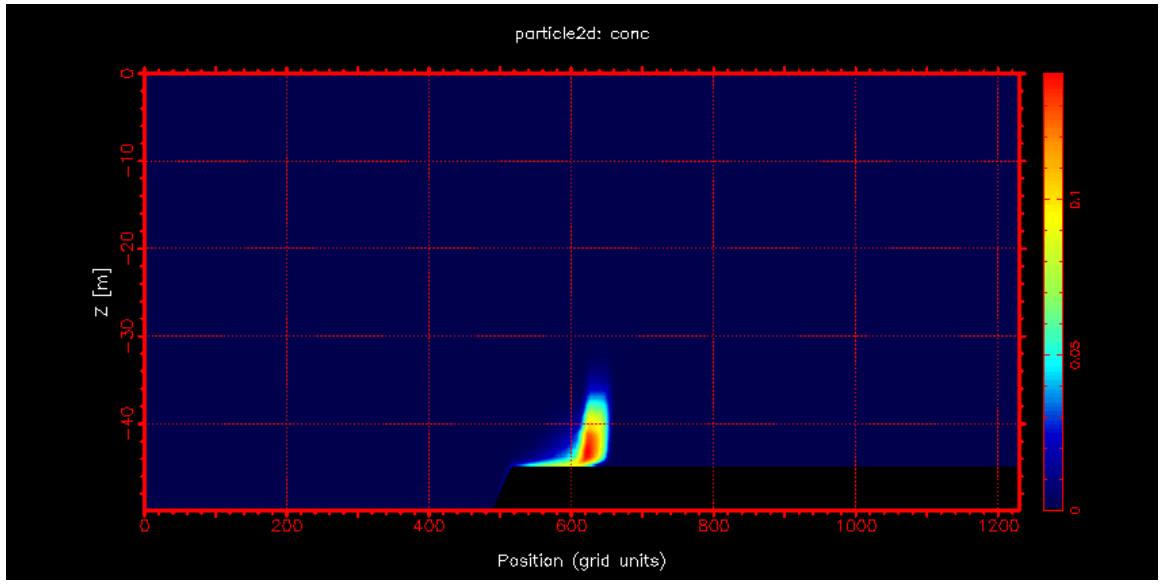
U = 0.1 m/s, S = 0.1, T = 1200 s



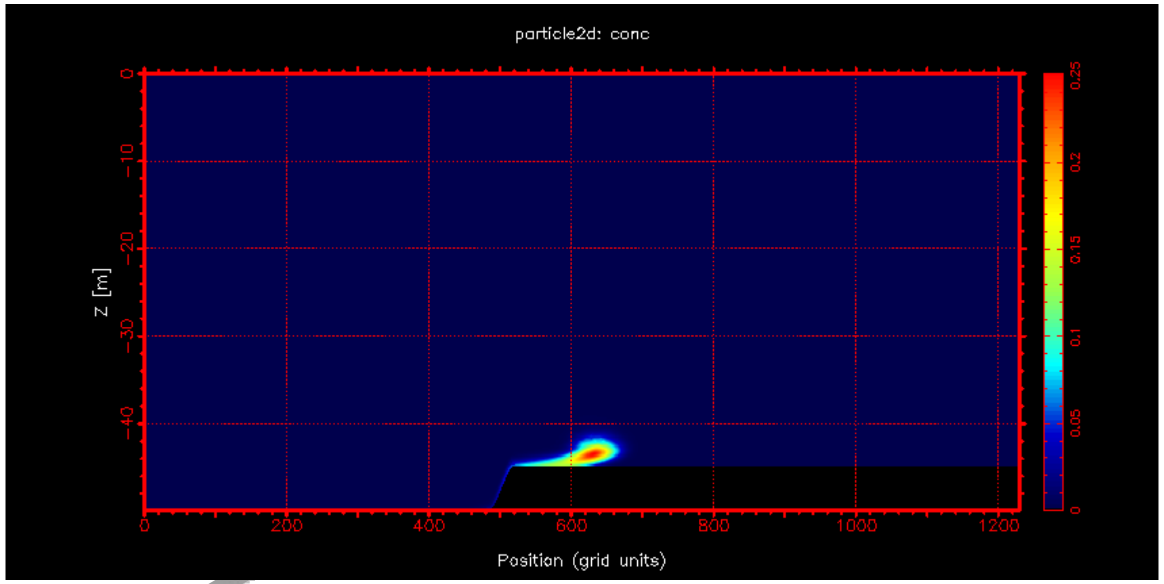
U = 0.75 m/s, S = 0.1, T = 160 s



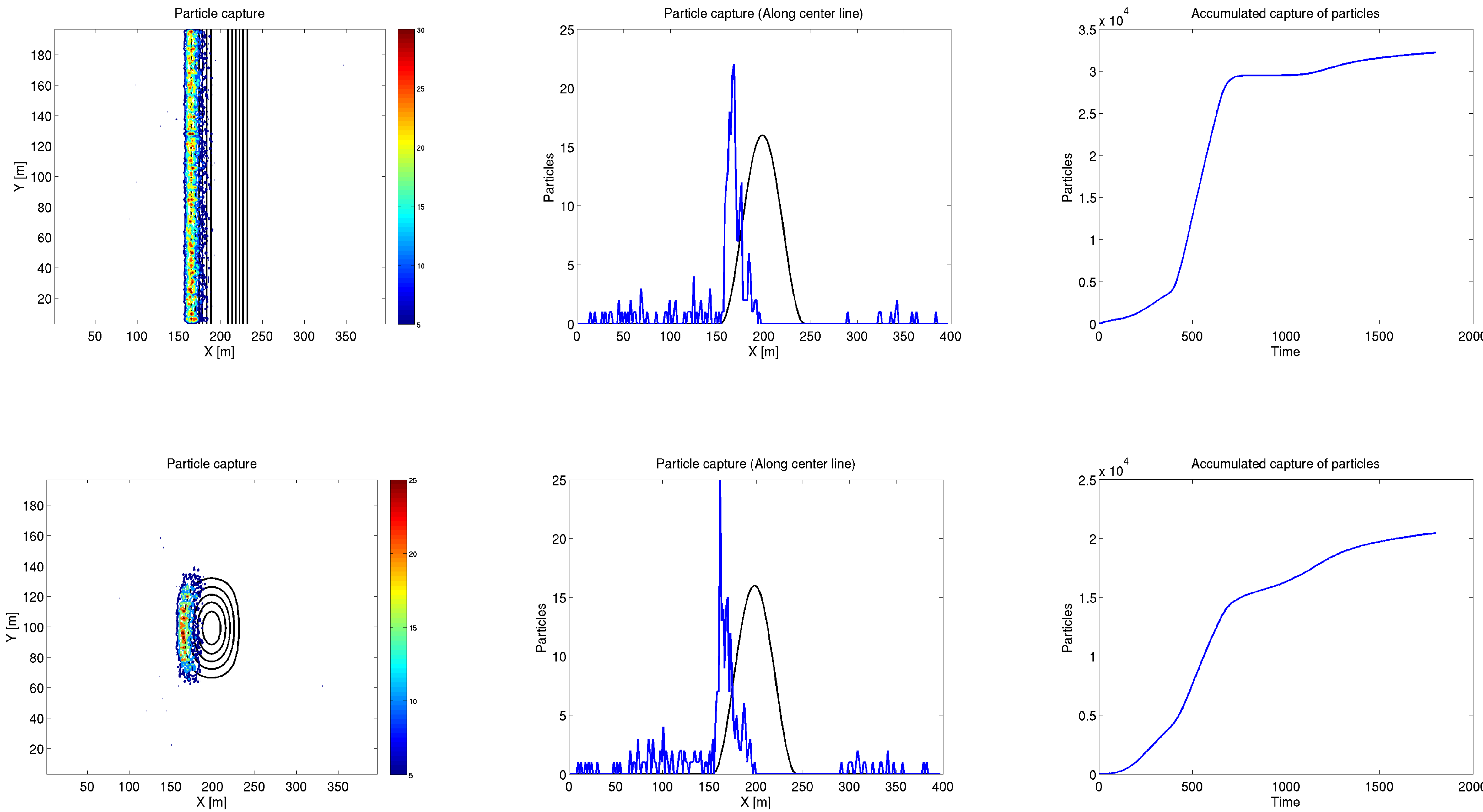
U = 0.1 m/s, S = 1.0, T = 1200 s



U = 0.75 m/s, S = 1.0, T = 160 s



3D simulations – ridge vs. sea mount



Summary

- Several unanswered questions about parameters governing formation of cold water reefs
- High resolution modeling is required for accurate particle tracking near reef structures
  - High resolution reduce need for high order time stepping and interpolation methods
- Further tests are needed to examine the significance of current speed and slope steepness
- Test indicate that feeding efficiency is an important parameter for optimal settlement location

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BOM: Equations for fluid flow

$$\nabla \cdot \vec{U} + \frac{\partial W}{\partial z} = 0 \quad ; \qquad \rho g = -\frac{\partial P}{\partial z} \quad ; \qquad \rho = \rho(S, T)$$

$$\frac{\partial U}{\partial t} + \vec{U} \cdot \nabla U + W \frac{\partial U}{\partial z} - fV = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial U}{\partial z}\right) + F_x$$

$$\frac{\partial V}{\partial t} + \vec{U} \cdot \nabla V + W \frac{\partial V}{\partial z} + fU = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial V}{\partial z}\right) + F_y$$

$$\frac{\partial T}{\partial t} + \vec{U} \cdot \nabla T + W \frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial T}{\partial z}\right) + F_T$$

$$\frac{\partial S}{\partial t} + \vec{U} \cdot \nabla S + W \frac{\partial S}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial S}{\partial z}\right) + F_S$$

Horizontal eddy vorticity and diffusivity terms

$$F_{x,y} = \frac{\partial}{\partial x}\left(A_M \frac{\partial(U,V))}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_M \frac{\partial(U,V))}{\partial y}\right)$$

$$F_{T,S} = \frac{\partial}{\partial x}\left(A_H \frac{\partial(T,S))}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H \frac{\partial(T,S))}{\partial y}\right)$$

$$(A_M, A_H) = (C_M, C_H)\Delta x \Delta y \frac{1}{2}\left[\left(\frac{\partial U}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right) + \left(\frac{\partial V}{\partial y}\right)^2\right]^{\frac{1}{2}}$$

Thank you for your attention!

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Future work

- Test different current speeds and reef profiles
  - Is there an optimal slope steepness related to different current speeds?
  - Include a background stratification
- How does a coral reef influence downstream flow, and distribution of reefs in a larger region?
- How efficient are corals at extracting nutrients from the water?
- How permeable is the coral reef?

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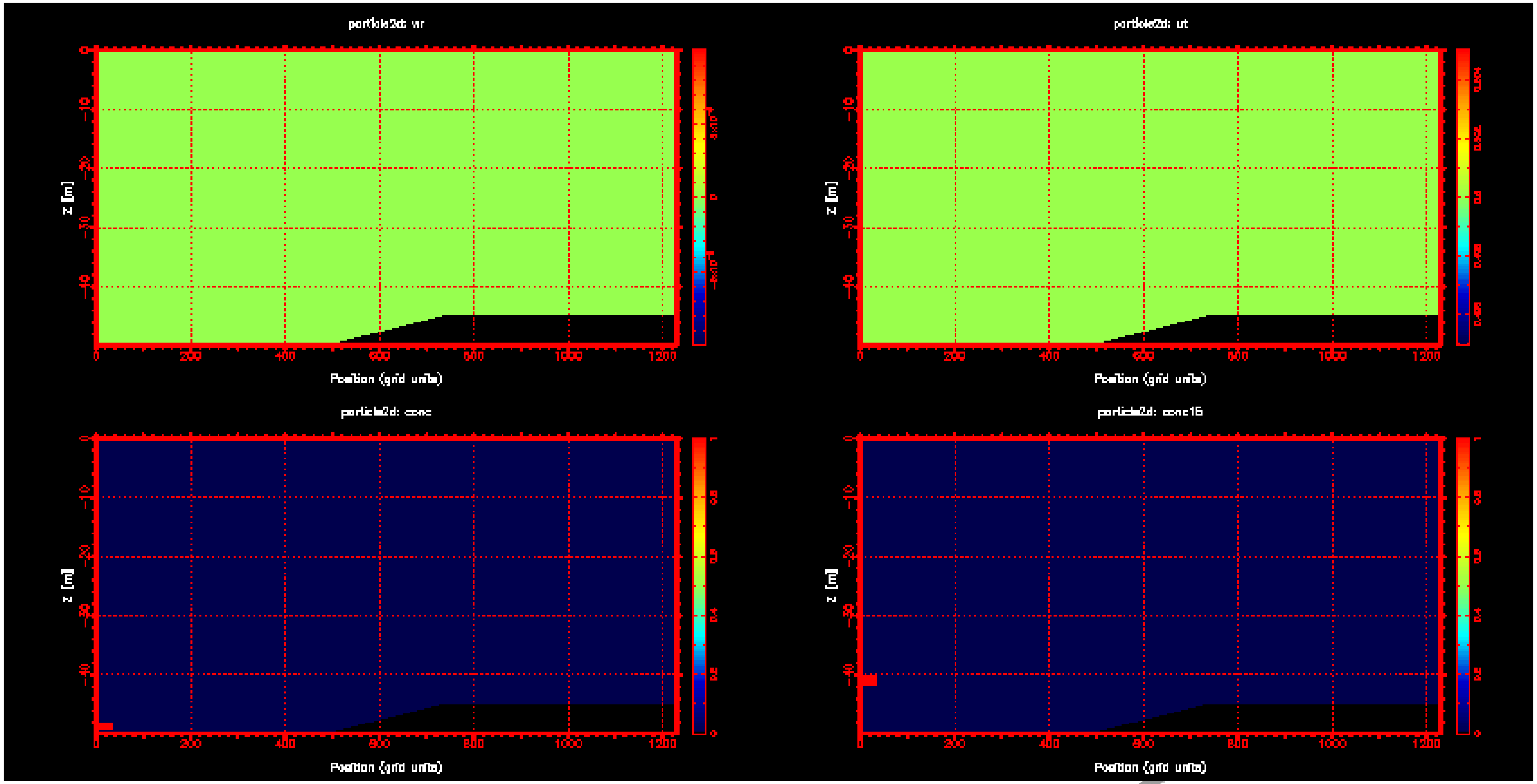
Diffusion of patch

Velocity U = 0.5 m/s; Steepness S = 0.1, T = 0 s



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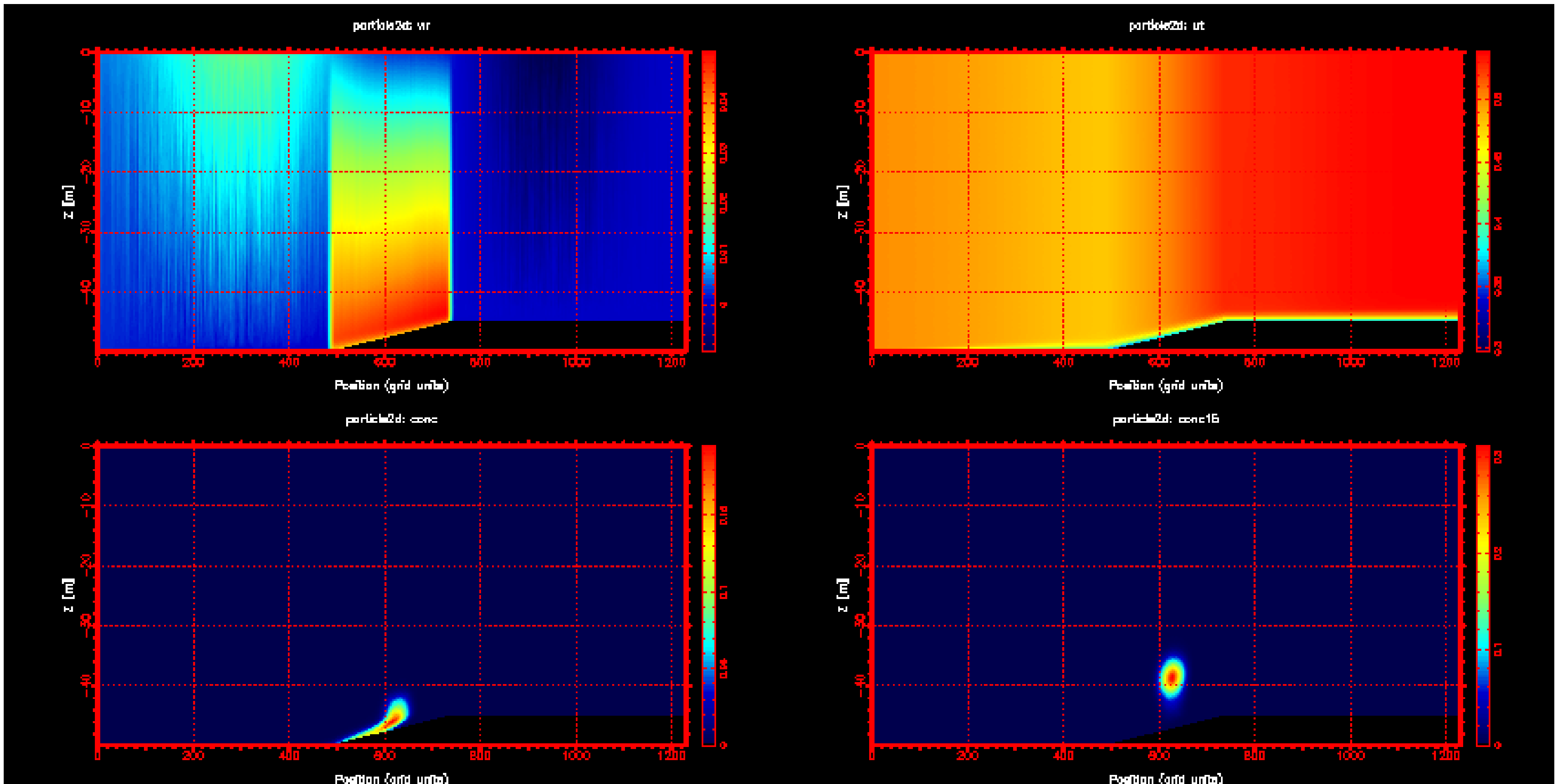
Diffusion of patch

Velocity U = 0.5 m/s; Steepness S = 0.1, T = 240 s



Dette er en forside

Dette er undertittelen

Dette er undertittelen

Denne forsiden har plass til bilde

Klikk på bildet
og lim inn et annet

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Dette er en vanlig side med overskrift

- Og en bulleliste
  - Med nivåer

På denne siden er det plass til

- Overskrift
- Bulletliste
- Ett bilde
  - Klikk på bildet for å lime inn et annen bilde

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Denne sidemalen har overskrift og objektplassholder

Side med mange bilder


Tekst


Tekst


Tekst


Tekst


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