ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Direct Numerical Simulation of Particle Settling in Model Estuaries

R. Henniger[(1)], L. Kleiser[(1)], E. Meiburg[(2)]

(1) Institute of Fluid Dynamics, ETH Zurich

(2) Department of Mechanical Engineering, UCSB

Outline

- Introduction / motivation
- Computational setup
  - flow configuration
  - governing equations and physical parameters
  - simulation code
- Results
  - freshwater / saltwater mixing
  - particle settling
- Conclusions and outlook

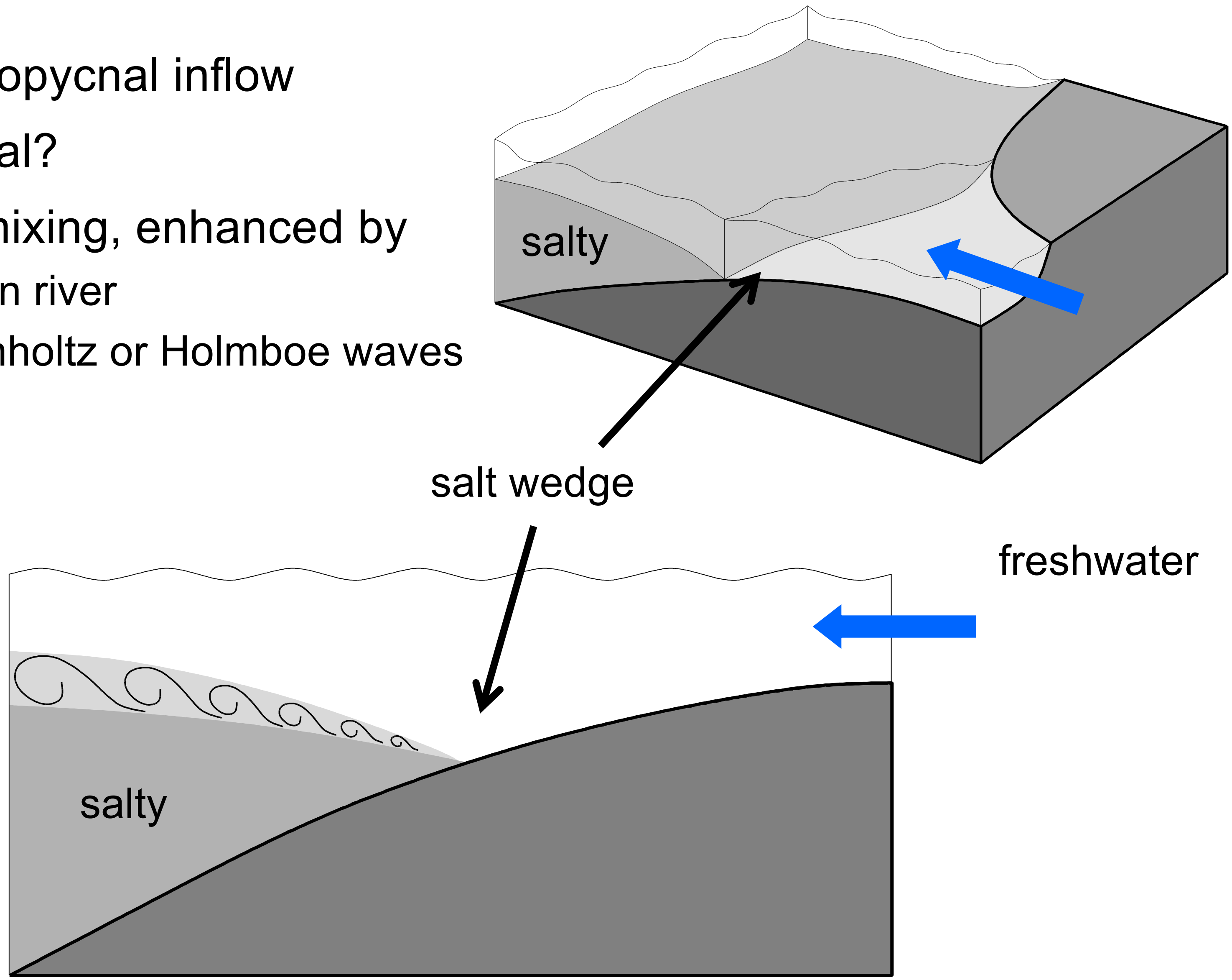
Introduction

- Estuary mouth
  - light fresh-water
  - heavy salt-water
- Suspended particles
  - e.g. sediment or pollutants
  - transport out to the ocean
  - particles settle and deposit
- Other influences
  - temperature profile
  - Coriolis effect, tide, …
- Focus of the present study: basic investigation of
  - freshwater / saltwater mixing
  - particle transport, particle settling and particle deposition

Magdalena River (Colombia)

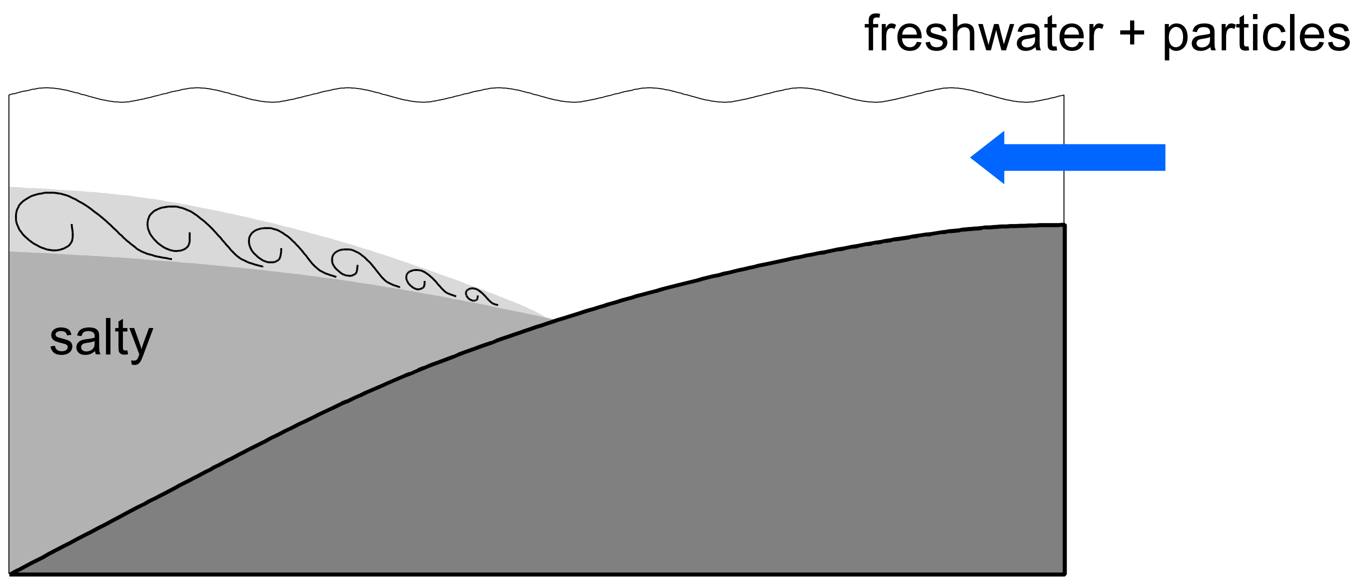
Freshwater / saltwater mixing

- Typically hypopycnal inflow
- (Super-)critical?
- Convective mixing, enhanced by
  - turbulence in river
  - Kelvin-Helmholtz or Holmboe waves

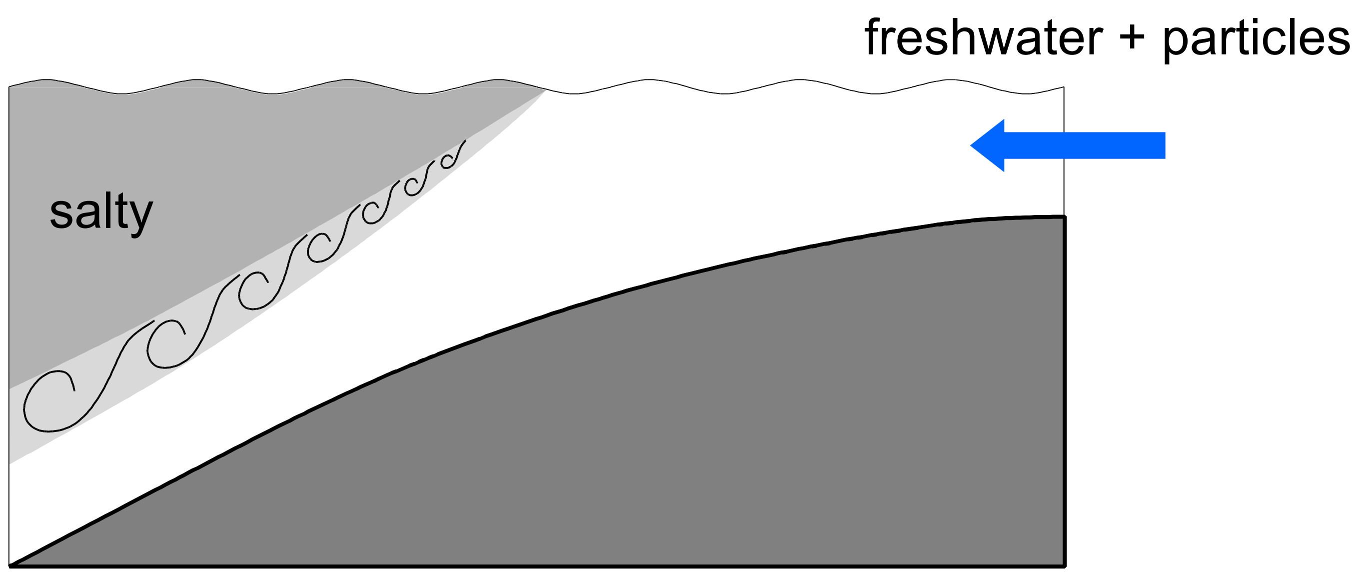


Particle load

- hypopycnal:



- hyperpycnal:



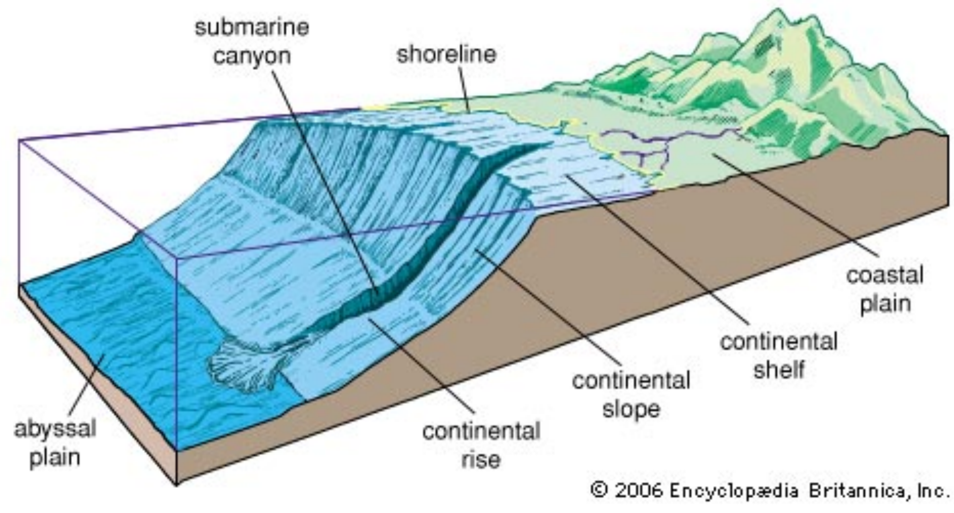
Particle transport

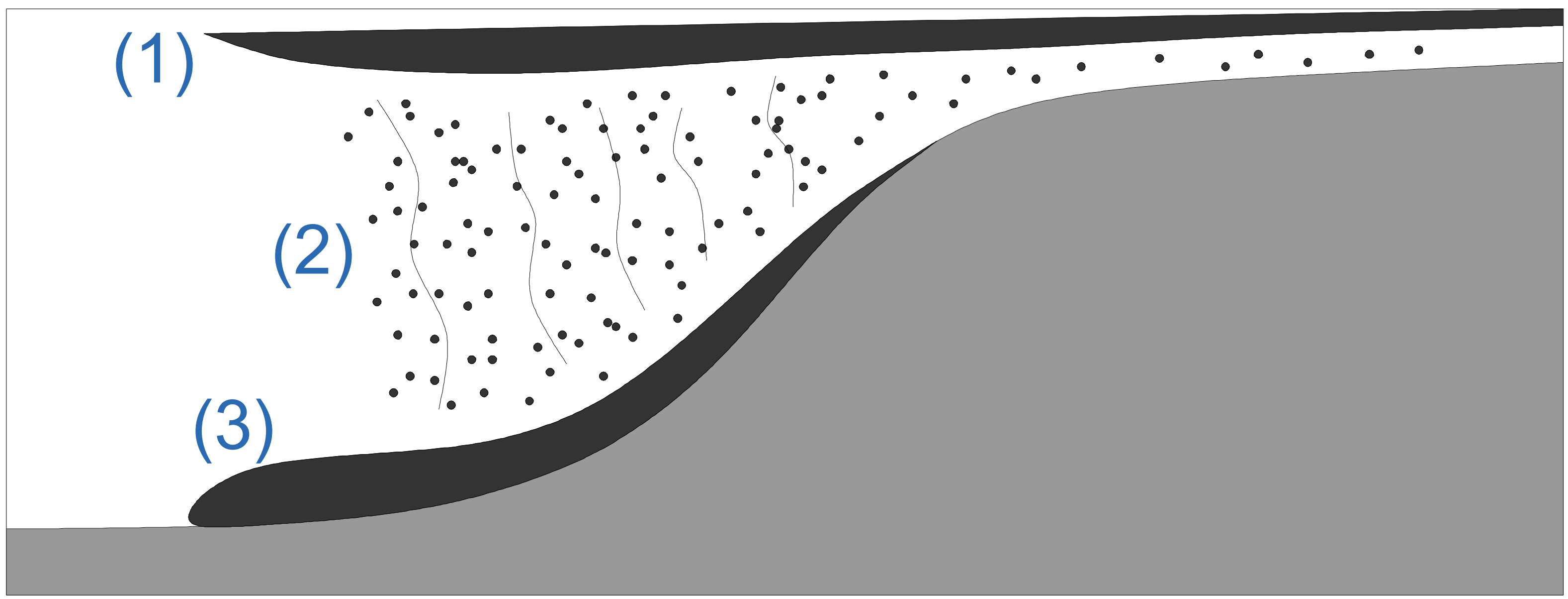
(1) Surface plume

(2) (Enhanced) particle settling

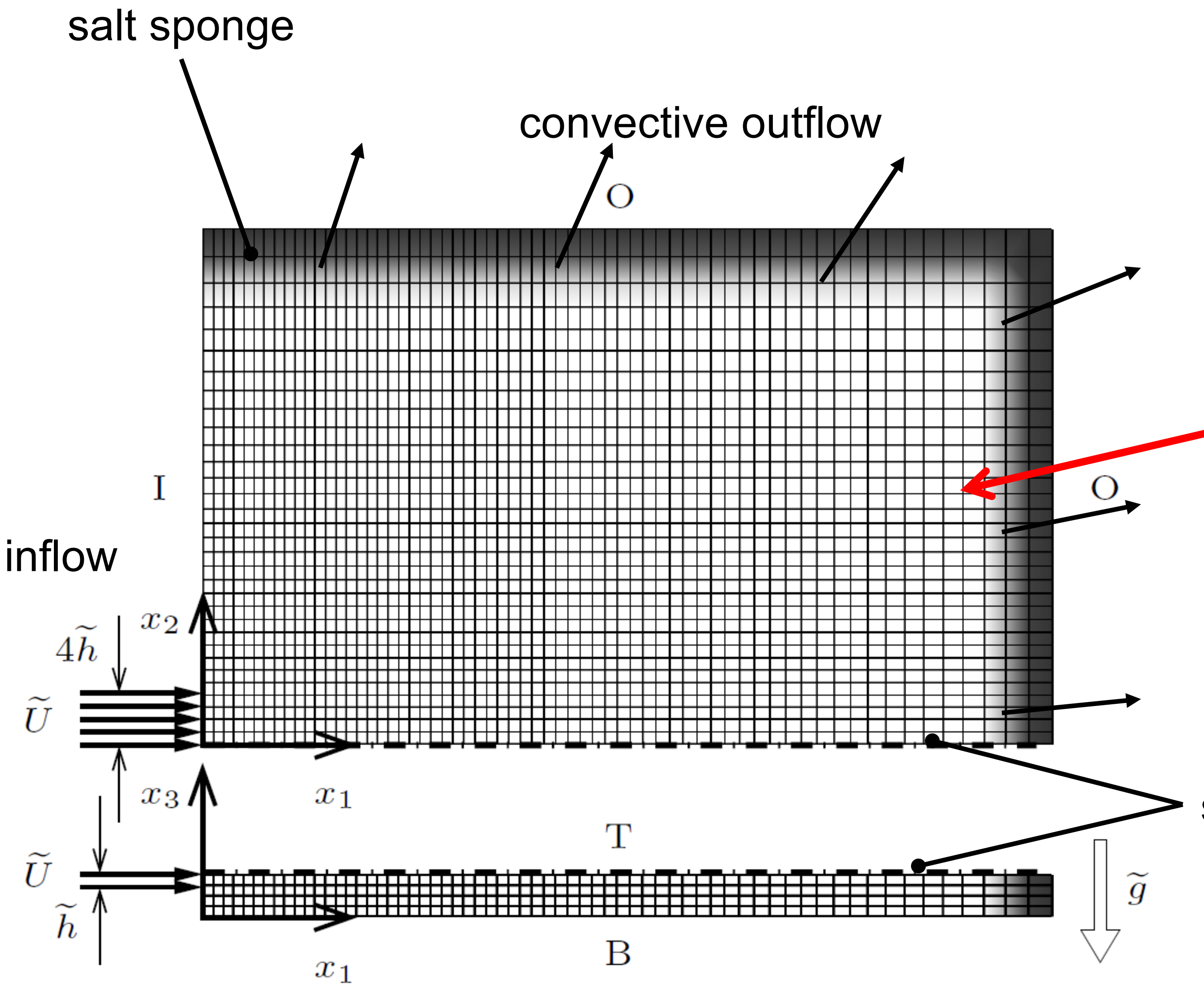
- flocculation?
- turbulence enhanced settling?

(3) Bottom propagating turbidity current





Model estuary configuration



Governing equations, non-dimensional

- Incompressible Navier-Stokes and concentration transport equations (in Boussinesq regime)

$$\nabla \cdot u = 0$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\nabla p + \frac{1}{Re} \Delta u + e^{\mathrm{g}} \sum_k Ri_k c_k$$

$$\frac{\partial c_k}{\partial t} + \left((u + u_k^{\mathrm{s}} e^{\mathrm{g}}) \cdot \nabla \right) c_k = \frac{1}{Re\, Sc_k} \Delta c_k, \quad c_k \in [0,1], \quad k = 1,2$$

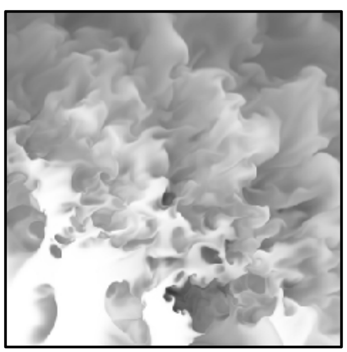
- Reynolds number: $Re = \widetilde{U}\widetilde{h}/\widetilde{\nu}$
- Schmidt number: $Sc = \widetilde{\nu}/\widetilde{d}$
- Richardson number: $Ri = \widetilde{g}'\widetilde{h}/\widetilde{U}^2 \qquad \widetilde{g}' = \frac{\Delta\widetilde{\rho}}{\overline{\widetilde{\rho}}}\widetilde{g}$
- Particle settling velocity: $u^{\mathrm{s}} = \widetilde{u}^{\mathrm{s}}/\widetilde{U}$

Physical parameters

	reality	laboratory	simulation
Re	10^5-10^7	10^3-10^4	1500
Sc_{sal}	500-3000	500-3000	1
Sc_{part}	$> Sc_{\text{sal}}$	$> Sc_{\text{sal}}$	2
Ri_{sal}	0.5-1	0.5-1	0.5
Ri_{part}	< 0.05	< 0.05	0.05
$-u^s/U$	$< 10^{-2}$	$< 10^{-2}$	0.01-0.02

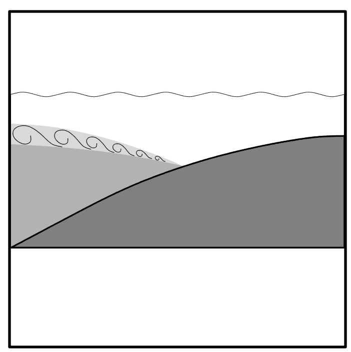
- ← turbulence (Re)
- ← "sharpness" of interfaces (Sc_{sal}, Sc_{part})
- ← sub-/supercritical flow (Ri_{sal})
- ← particle load (Ri_{part})
- ← particle plume extent ($-u^s/U$)

turbulence

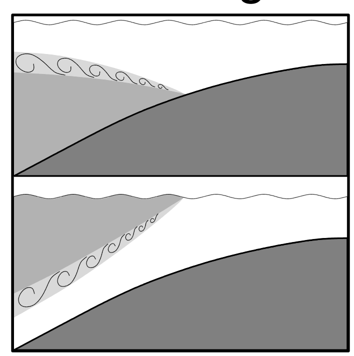


interfaces

inertial forces



loading



extent

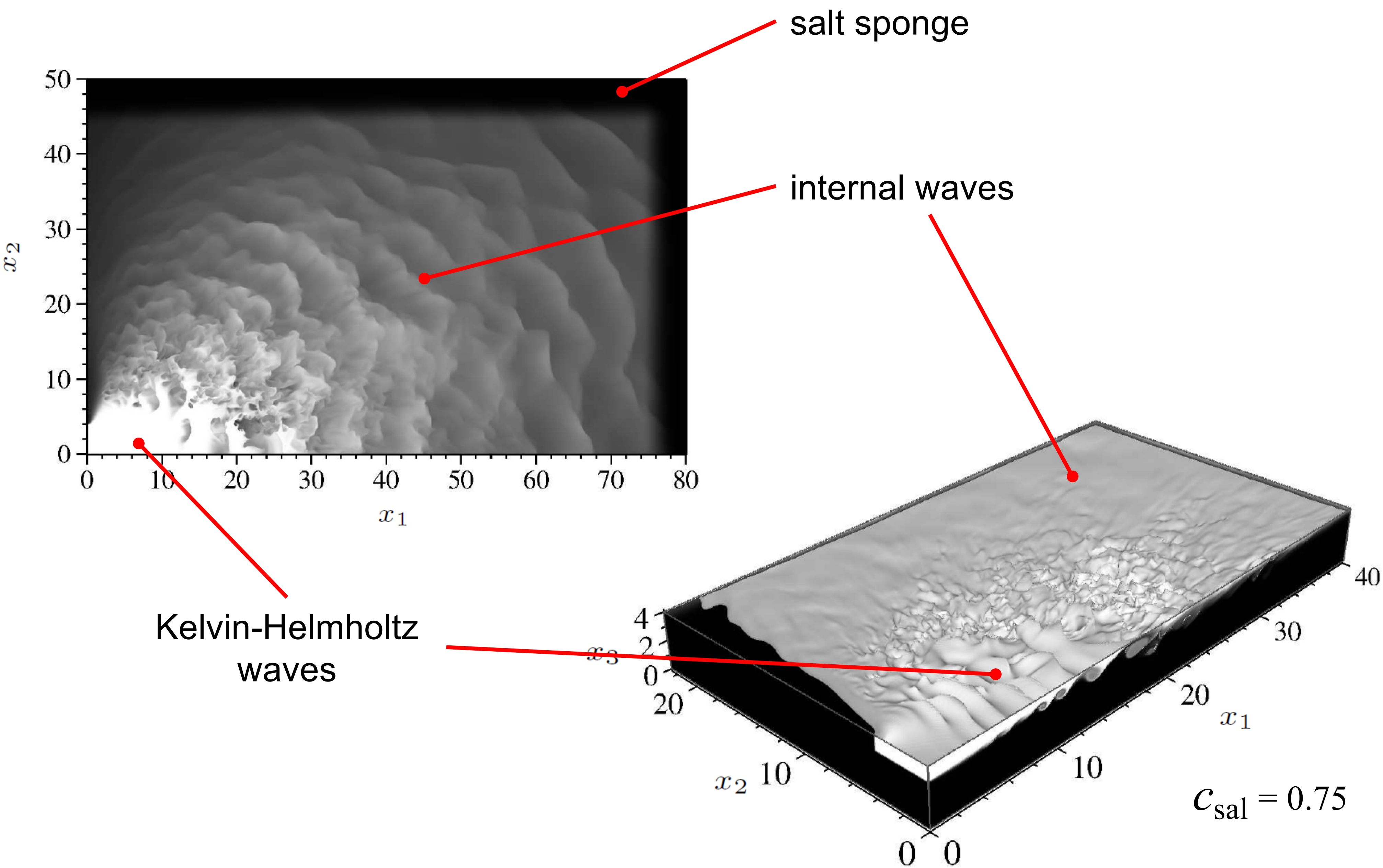
Newly developed simulation code (summary)

- Incompressible flows + active scalars
- Discretization
  - compact finite differences in space
  - explicit or semi-implicit time integration
- Massively parallel platform
  - 3D domain decomposition (>95% parallel efficiency)
  - sustained 16% peak performance on Cray XT
  - scalability tested to up to 8000 cores and 17 billion grid points
- Validation
  - convergence orders in time and space
  - convergence properties of iterative solvers
  - temporal and spatial growth of eigenmodes
    - channel flow
    - shear layer flows with passive scalar
  - transitional and turbulent channel flow (vs. P. Schlatter)
  - particle-driven gravity current (vs. F. Necker)
  - parallel scaling properties

Results:

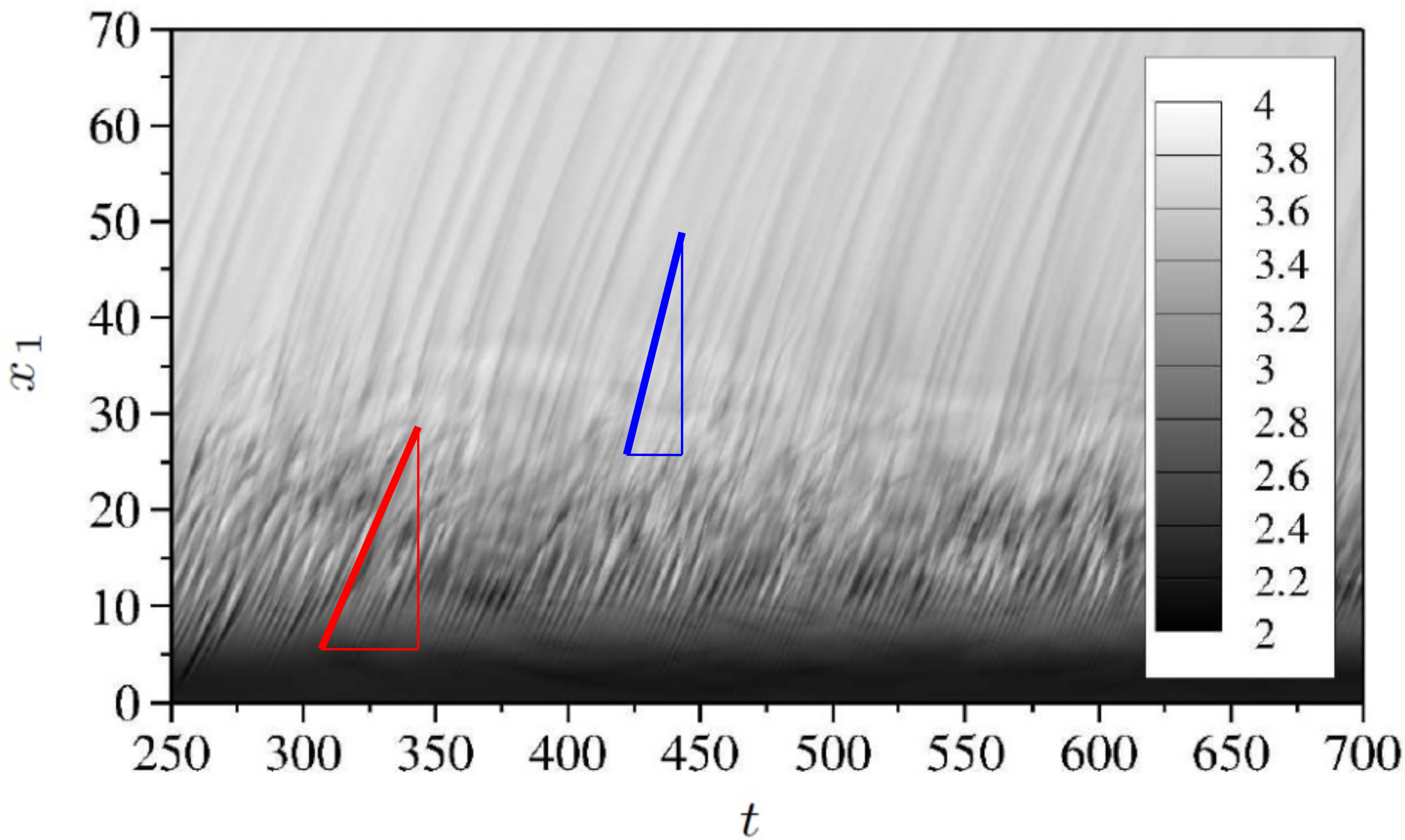
freshwater / saltwater mixing

Freshwater current



Group velocity of internal waves $u_{\text{wave}} = \frac{\partial x_{\text{wave}}}{\partial t}$

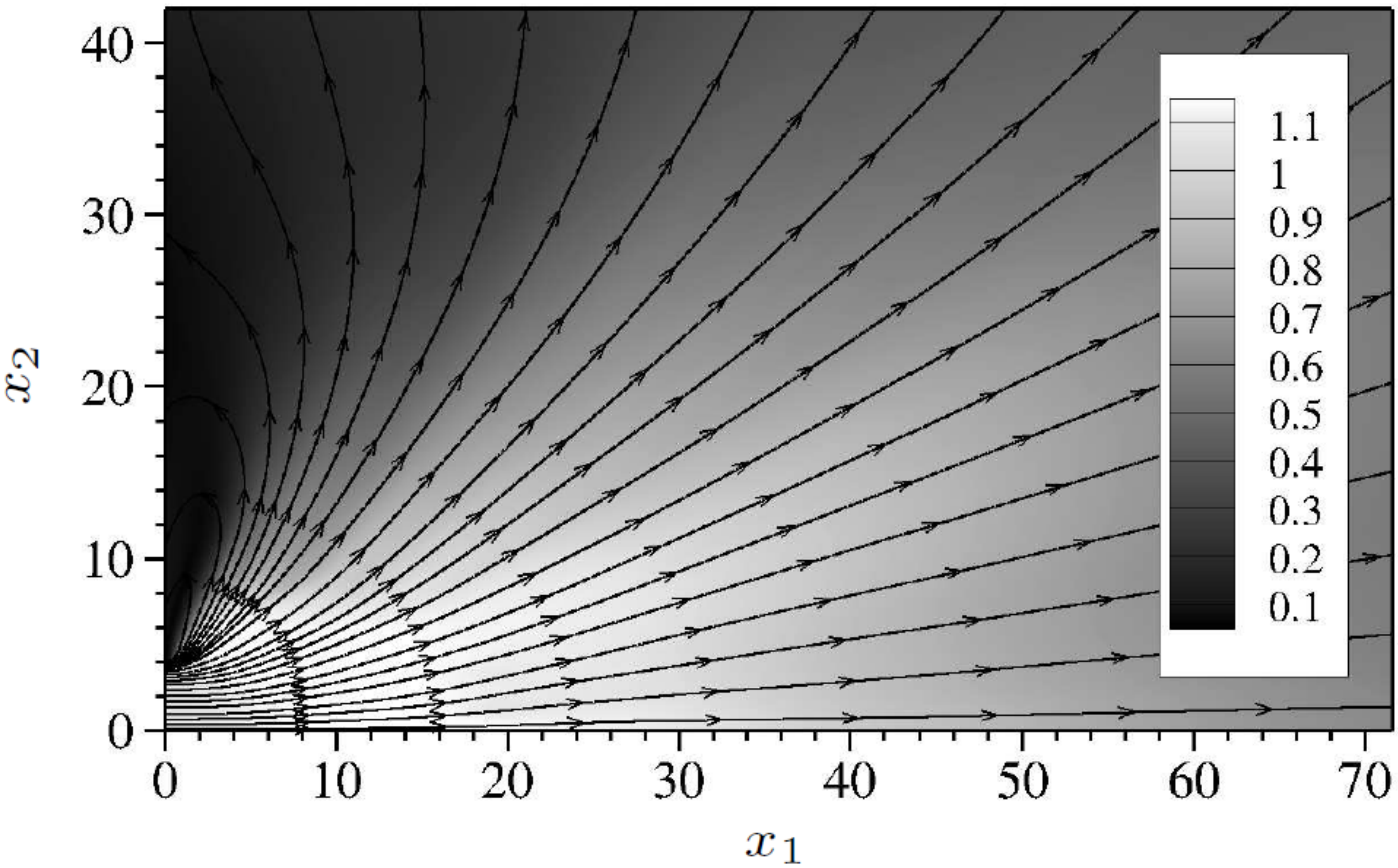
(measured with potential energy at $y = 0$)



$u_{\text{KH}} \approx 0.5 \ldots 0.6 \approx \frac{U}{2}$

$\frac{U}{2} \lessapprox u_{\text{wave}} \lessapprox U$

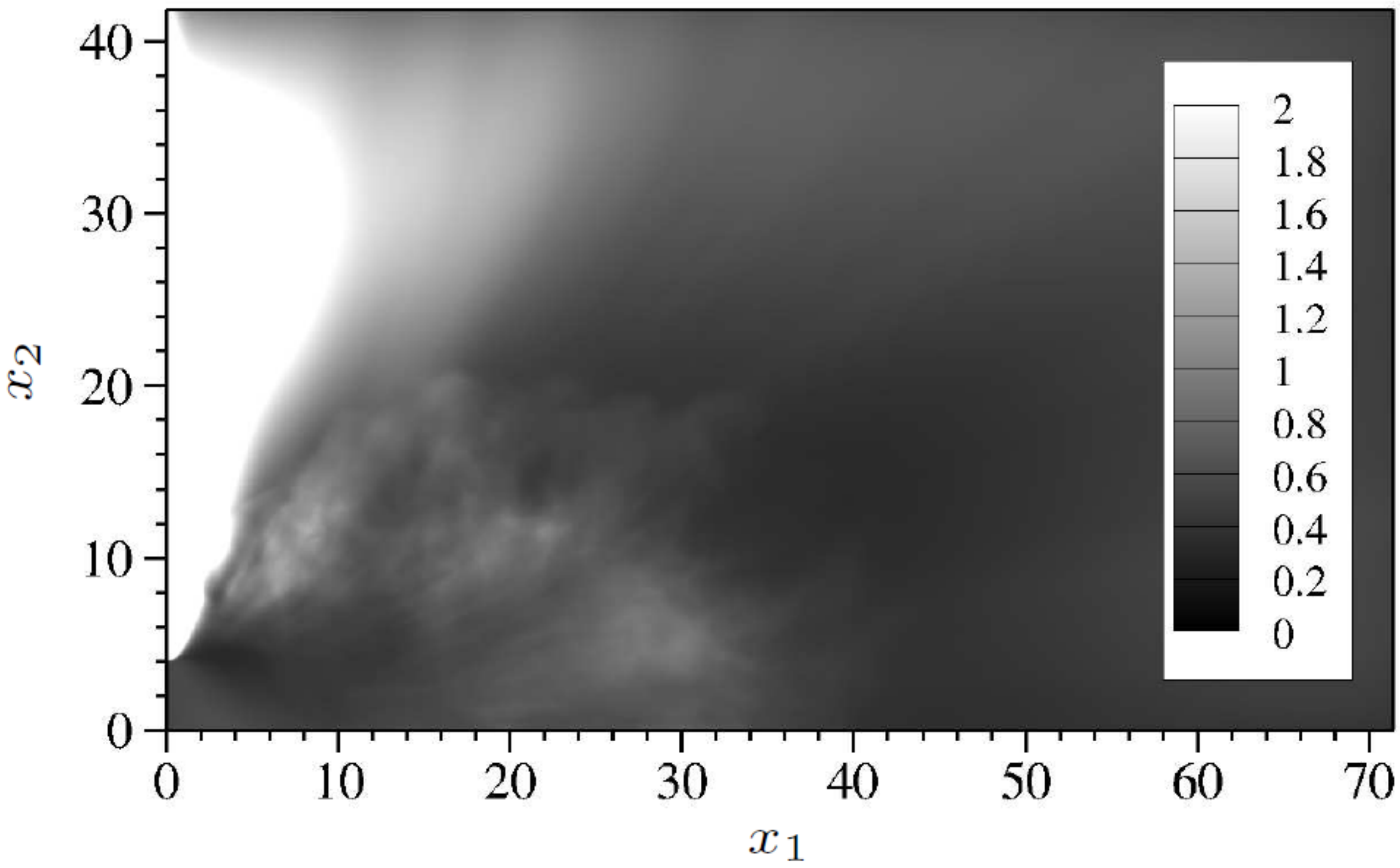
Streamlines on water surface



Sub-/supercritical flow

- kinetic vs. buoyant forces
- measured with *bulk* Richardson number

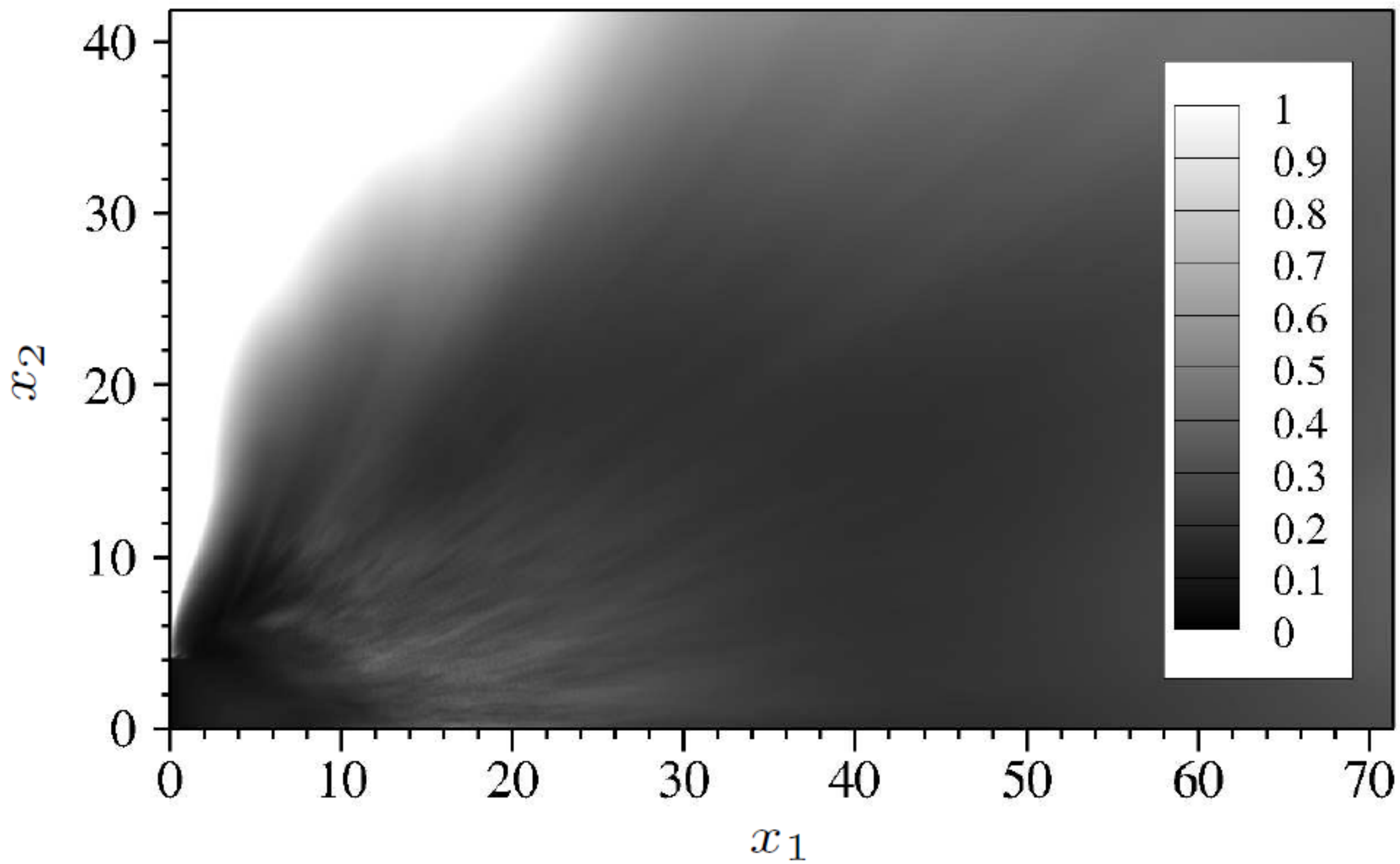
$$Ri_{\mathrm{b}} = \frac{Ri_{\mathrm{sal}} \langle \Delta c_{\mathrm{sal}} \rangle \overline{h}}{|\langle \Delta u \rangle|^2} = \frac{Ri_1 \int (C_{\mathrm{sal}} - \langle c_{\mathrm{sal}} \rangle)(L_3 - x_3) \mathrm{d}x_3}{\frac{1}{2} \int (\langle u_1 \rangle^2 + \langle u_2 \rangle^2 + \langle u_3 \rangle^2) \mathrm{d}x_3}$$



Interface stability

- shear stress vs. density difference
- measured with *gradient* Richardson number

$$Ri_g = \frac{-Ri_{sal} \min_{x_3} \left\{ \frac{\partial \langle c_{sal} \rangle}{\partial x_3} \right\}}{\max_{x_3} \left\{ \left(\frac{\partial \langle u_1 \rangle}{\partial x_3} \right)^2 + \left(\frac{\partial \langle u_2 \rangle}{\partial x_3} \right)^2 + \left(\frac{\partial \langle u_3 \rangle}{\partial x_3} \right)^2 \right\}}$$



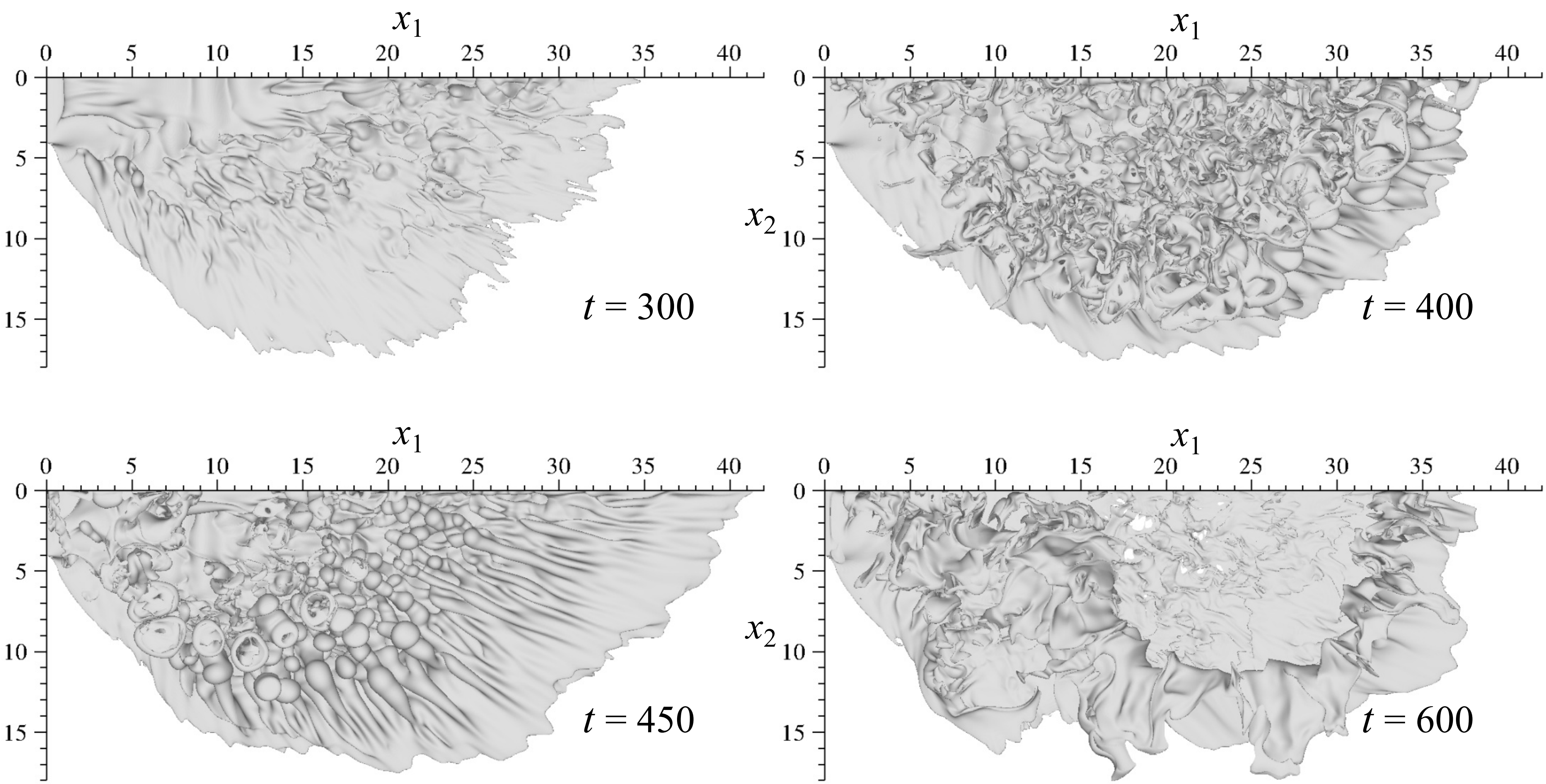
Results:

particle settling

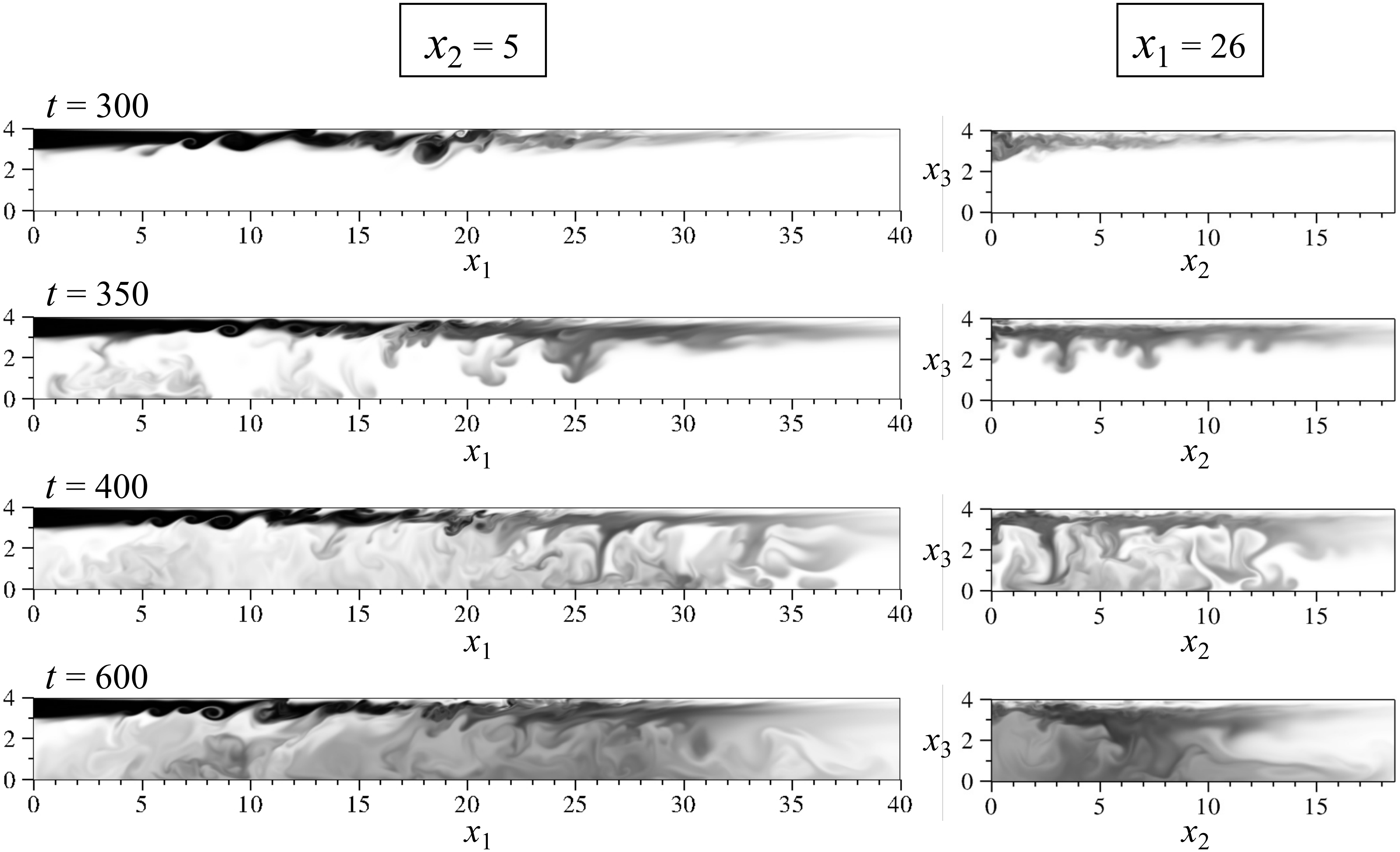
Particle settling

- Three different settling velocities $u^s/U = -0.02, -0.015, -0.01$
- Qualitative agreement with laboratory experiments?
  - Maxworthy (JFM, 1999)
  - Parsons et al. (Sedimentology, 2001)
  - McCool & Parsons (Cont. Shelf Res., 2004)
- Open questions
  - extent of particle plume?
  - particle settling modes (transient, steady state)?
  - effective settling velocity?
  - deposit profile?

Particle plume $u^{s}/U = -0.02, \ c_{part} = 0.1$

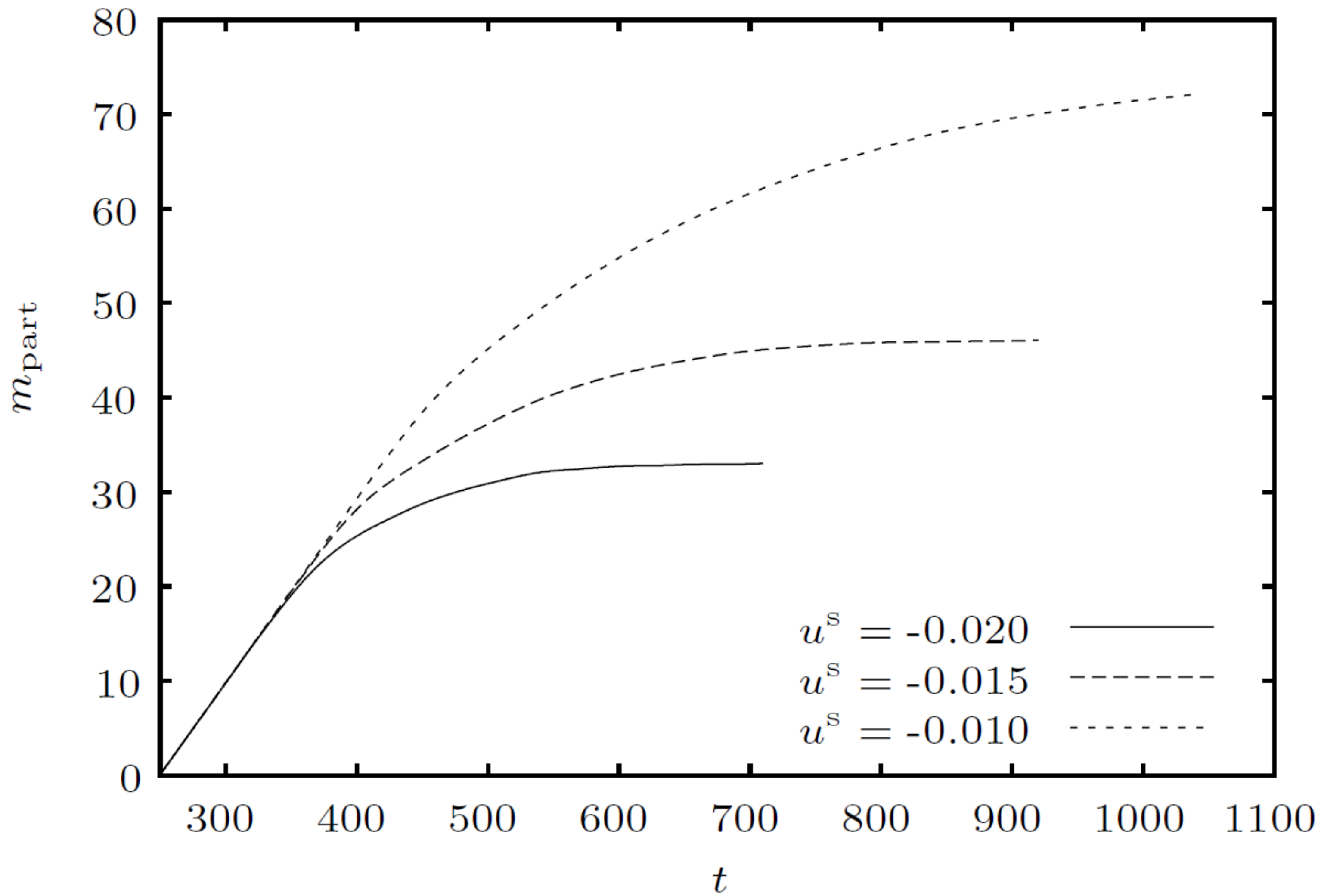


Convective particle settling $u^s/U = -0.02$



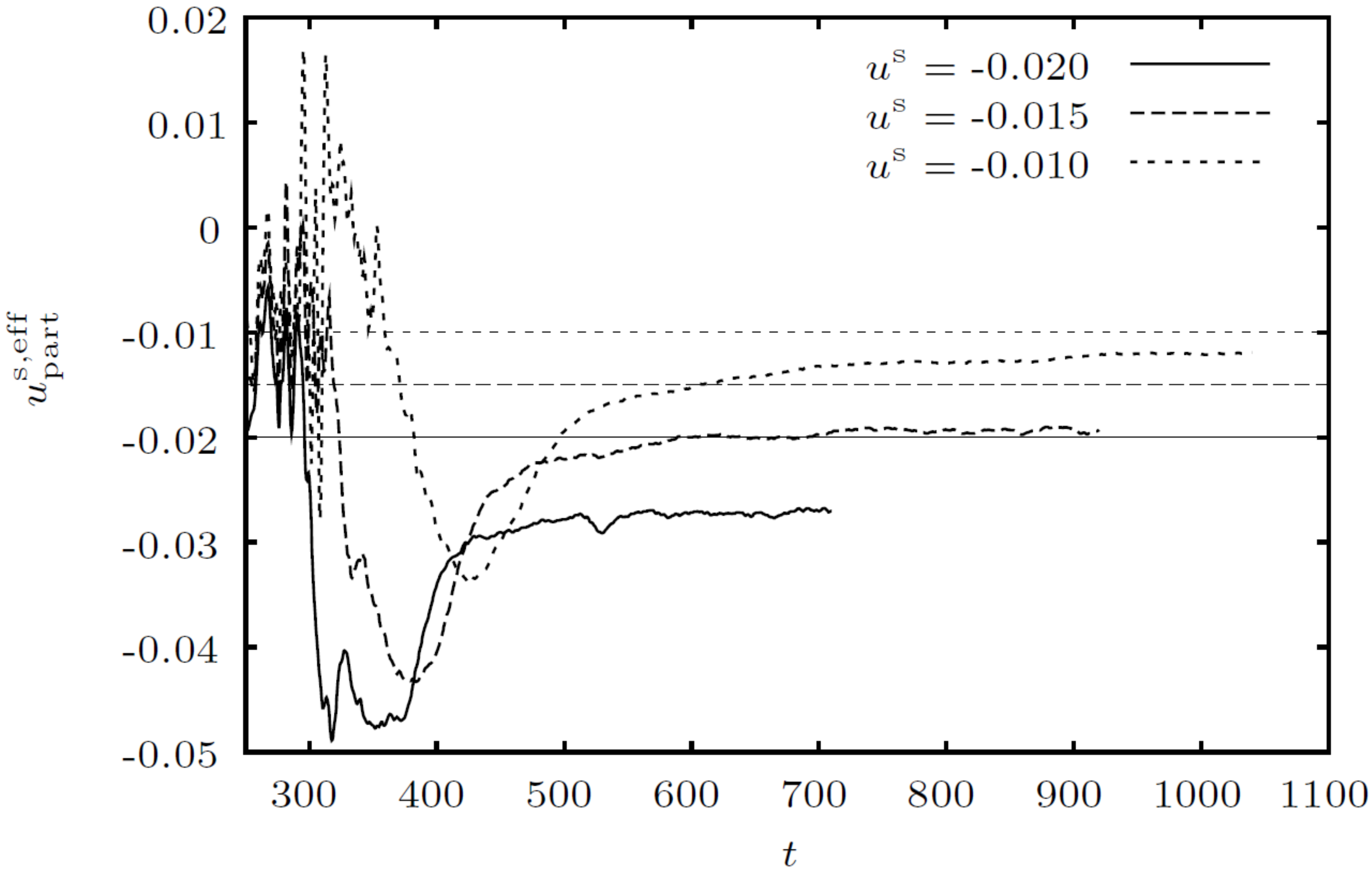
Particle mass

$$m_{\text{part}} = Ri_{\text{part}} \int c_{\text{part}} \mathrm{d}V$$



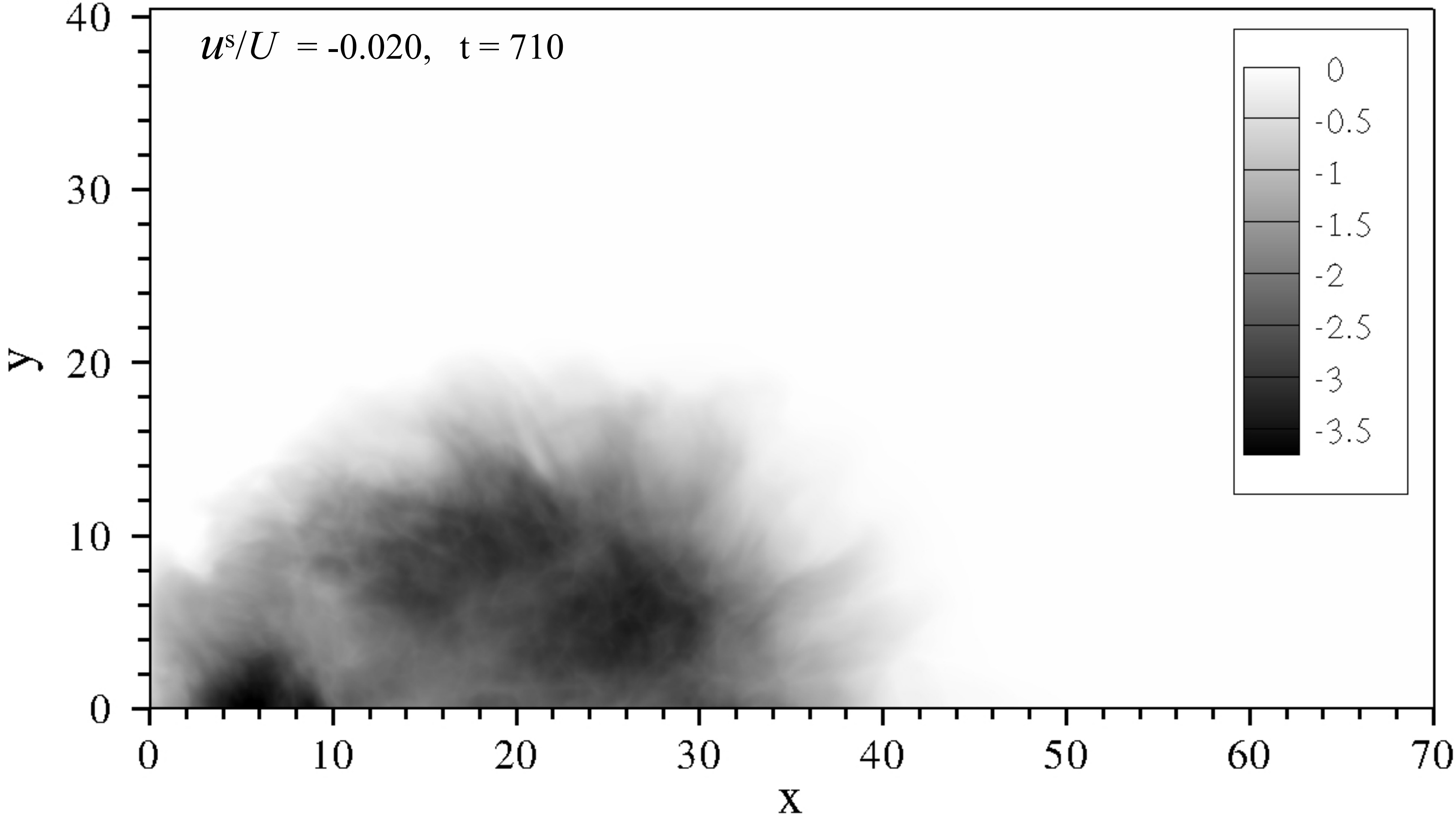
Effective particle settling velocity

$$u_{\mathrm{part}}^{\mathrm{s,eff}} = \int c_{\mathrm{part}}(u_3 + u_{\mathrm{part}}^{\mathrm{s}})\mathrm{d}V / \int c_{\mathrm{part}}\mathrm{d}V$$



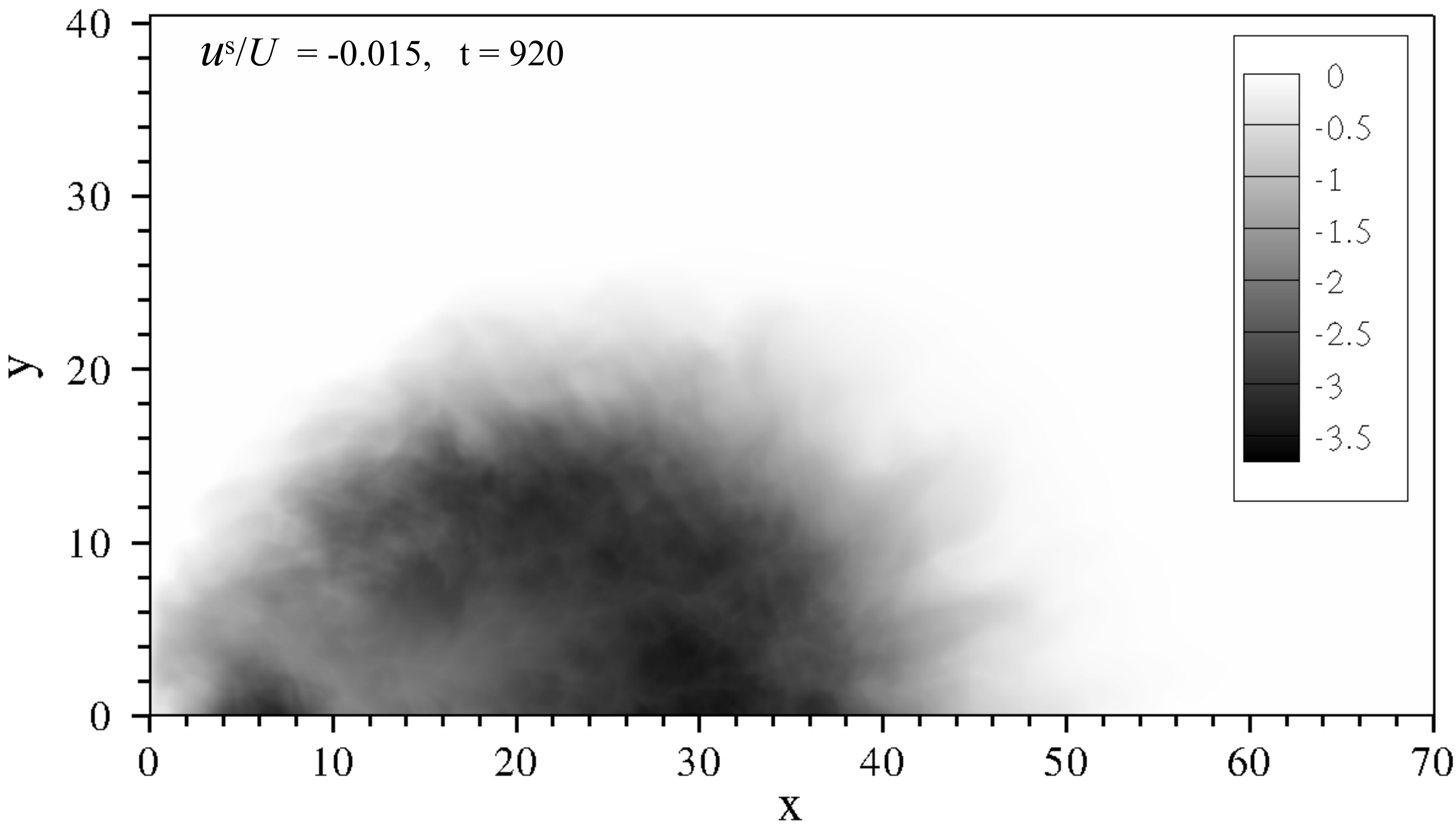
Particle Deposit

$$D = \int c_{\text{part}}(x_3 = 0) u^{\text{s}}_{\text{part}} \, \mathrm{d}t$$



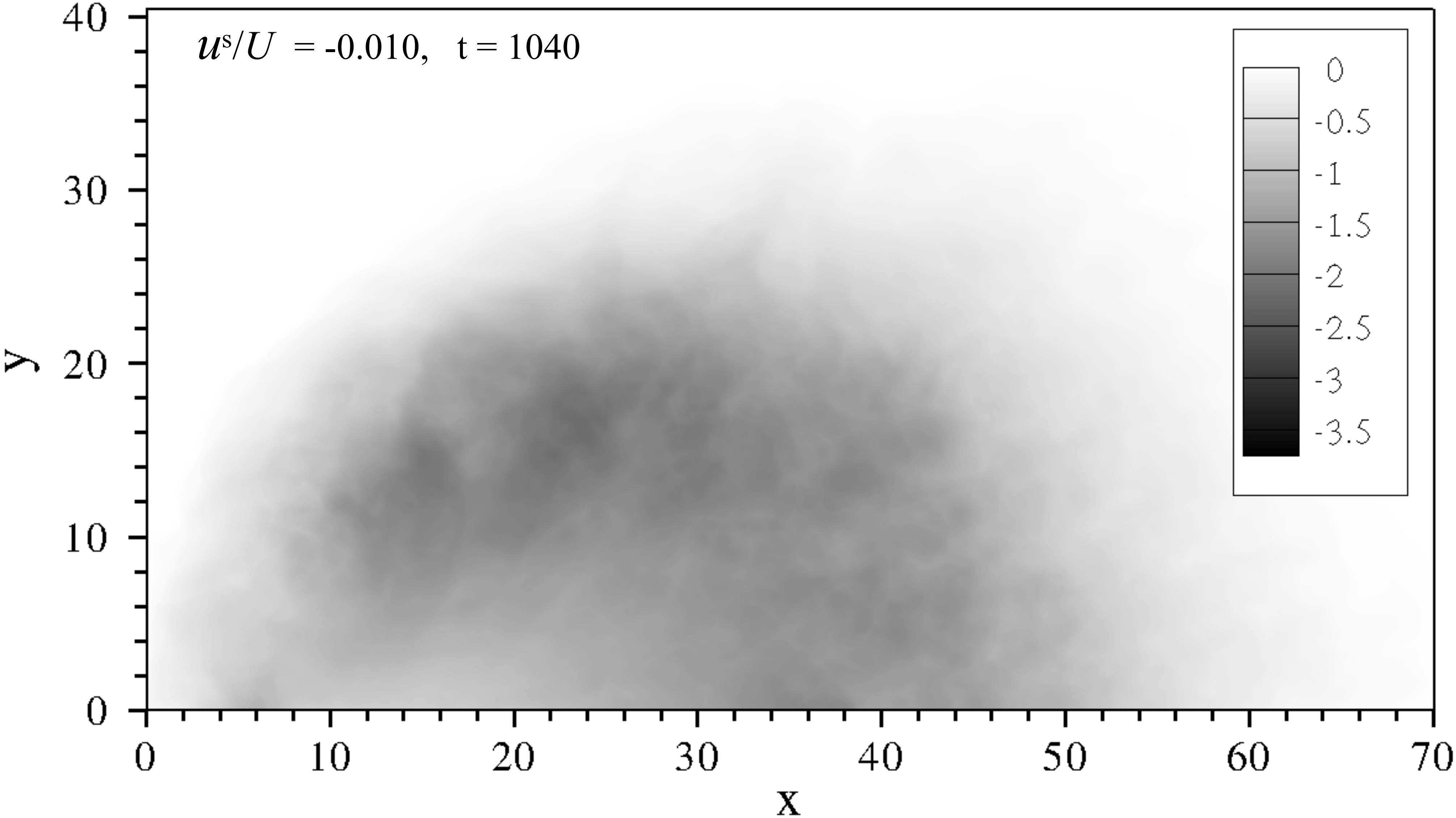
Particle Deposit

$$D = \int c_{\mathrm{part}}(x_3 = 0)\, u^{\mathrm{s}}_{\mathrm{part}}\, \mathrm{d}t$$



Particle Deposit

$$D = \int c_{\mathrm{part}}(x_3 = 0)\, u^{\mathrm{s}}_{\mathrm{part}}\, \mathrm{d}t$$



Conclusions

- Definition of simulation setup
  - parameters
  - inflow
  - boundary conditions
  - sponge zones, etc.
- Results: Basic effects compare well with laboratory experiments
  - freshwater-brine mixing
  - finger convection
  - enhanced convective particle settling
- Results obtained at moderate Re and Sc, accessible to DNS

Outlook

- Further increase of Re and Sc with LES in the future
- Implemented LES models:
  - ADM-RT model (filter model)
  - (HPF) Smagorinsky
  - (upwinding)
- Validation of LES to be completed
- Further option: more complex domains e.g. by
  - orthogonal curvilinear grids
  - immersed boundary method
  - (immersed interface method)

Appendix