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Numerical Investigation of Entrainment of Turbulent Dense Currents

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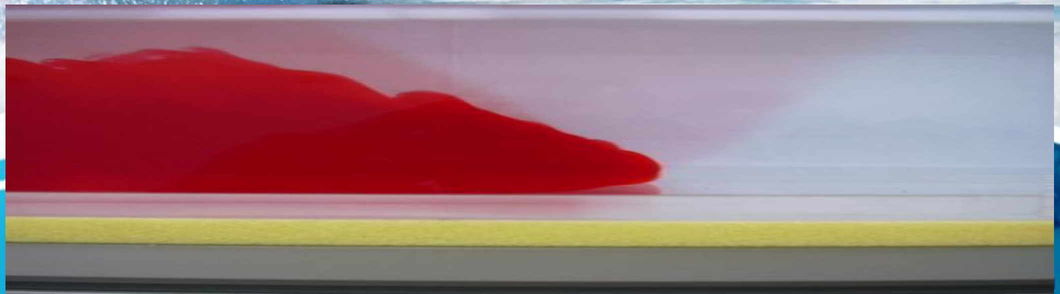
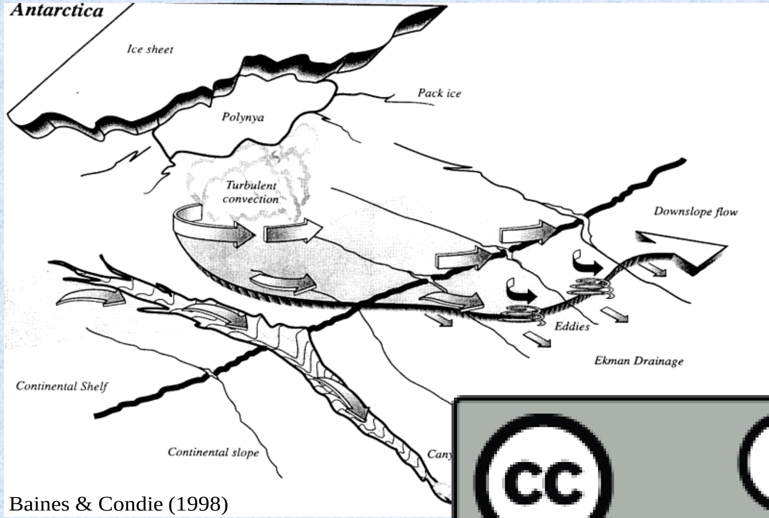
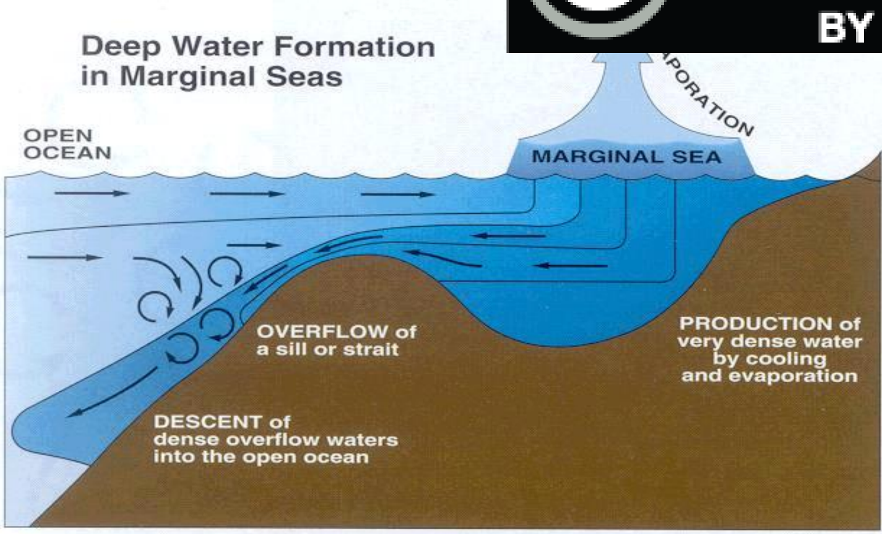


Turbulent Dense Currents

Density Current Formation



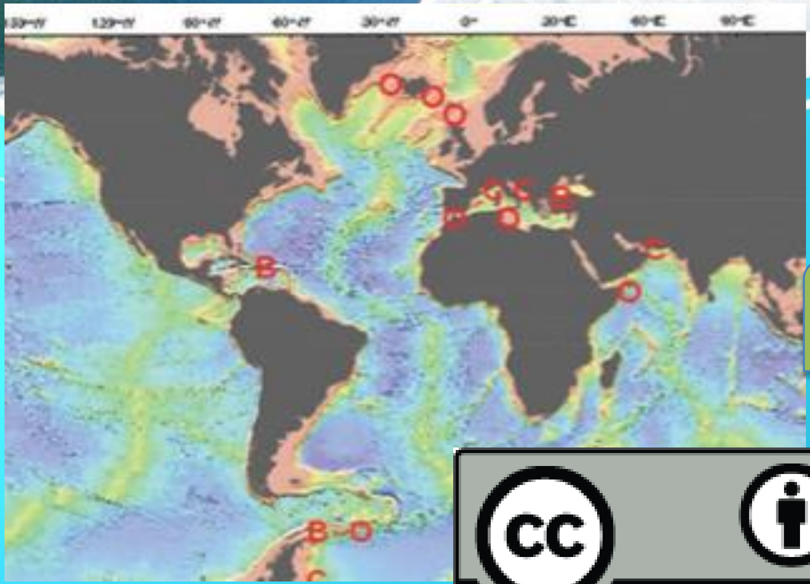
Baines & Condie (1998)



- Gravity current overflows: Major pathway for deep water replenishment - ocean circulation and climate predictions [Legg et al., 2009].
- Shear instabilities: interfacial layer between dense waters and ambient waters.
- Mixing controls the downstream evolution of T and S, the equilibrated outflow's timate composition is controlled by ostream turbulence.
- roper accounting of processes controlling cumulative entrainment is a prerequisite for predicting terminal depth and volume flux, properties that can dynamically alter global circulation patterns.

Global coupled ocean-atmospheric model (Grid-100km) cannot resolve overflows

Motivation



Significance of Overflows

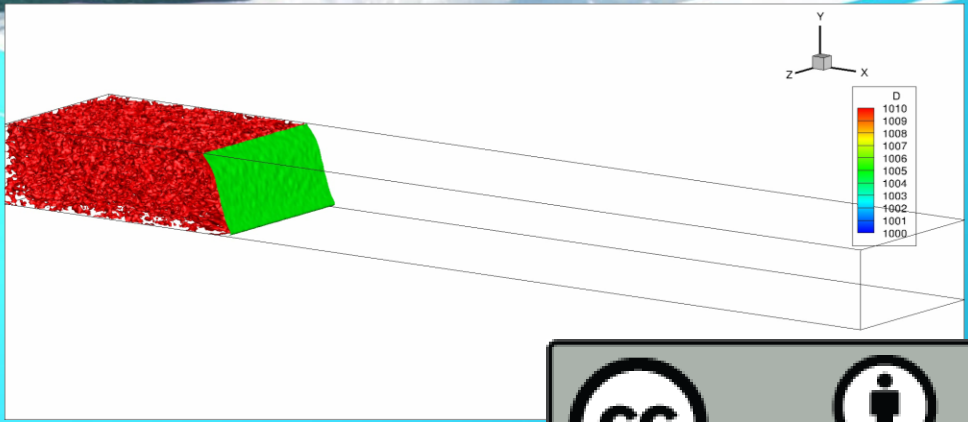
Overflow Representation in Models seriously deficient: Numerical challenge

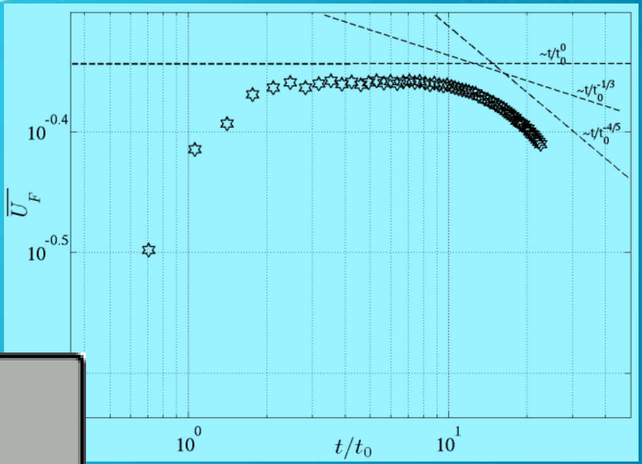
O: Overflow across a t[illegible] barrier from a regional basin into the open ocean (Nordic seas North Atlantic, Subtropical Med, Red seas)

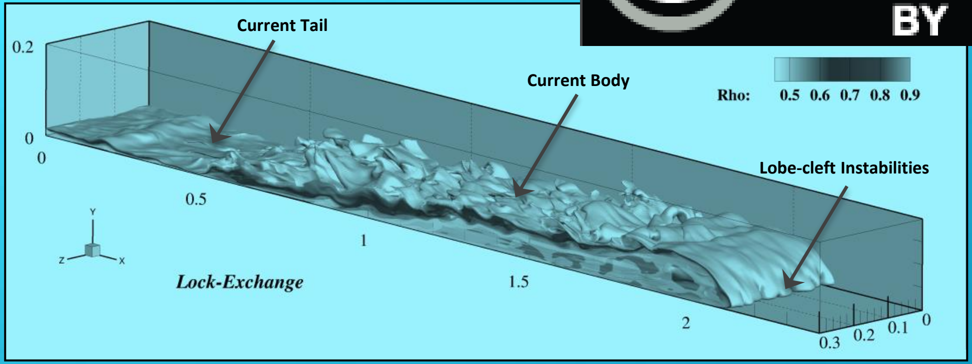
B: Open-ocean overflow into an isolated regional basin.

C: Cascade of dense water from a continental shelf into deep over over sloped sea floor (Antartica, Ross Seas)

Numerical Studies: Lock-exchange Release Density Currents







Shear instabilities (e.g. Kelvin-Helmoltz instabilities) are key for mixing in overflows (and lock-exchange)

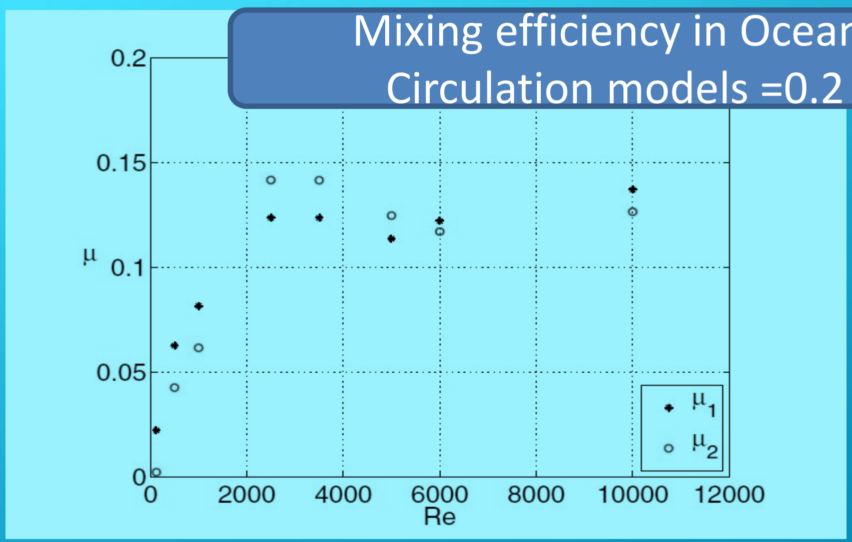
→ simulation corresponds to a laboratory scale current, not field scale! Reynolds numbers are Orders of magnitude smaller.

Scientific Questions

(1) What is the difference in Entrainment between lock-exchange and overflows ? LES/DNS

(2) What is governing physics for mixing in these lock-release and overflows ? Energetics (TKE production)

(3) How to bridge gap between field-studies , ocean circulation models and DNS/LES ?



Mixing efficiency in Ocean-Circulation models =0.2

Ilicak (2014) Ocean Modelling: Lock-exchange release flows (M.E. = irreversible mixing /irreversible mixing+dissipation)

Mixing Efficiency – Fraction of available energy released to K.E converted into irreversible increase of potential energy

Numerical Tool

Large-Eddy-Simulation

Finite-volume, Smagorinsky based 2nd order space & time. (EFM, 2016, review)

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j u_i) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu_{eff}\frac{\partial u_i}{\partial x_j}\right) + g_i\left(1 + \frac{\rho - \rho_a}{\rho_a}\right)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(u_j \bar{\rho}) = \frac{\partial}{\partial x_k}\left(\kappa_{eff}\frac{\partial \rho}{\partial x_k}\right)$$

$$\nu_{eff} = \nu + \nu_{sgs} \quad \text{and} \quad \kappa_{eff} = \frac{\nu_{sgs}}{Sc_t} + \frac{\nu}{Sc}$$

Direct-Numerical Simulation

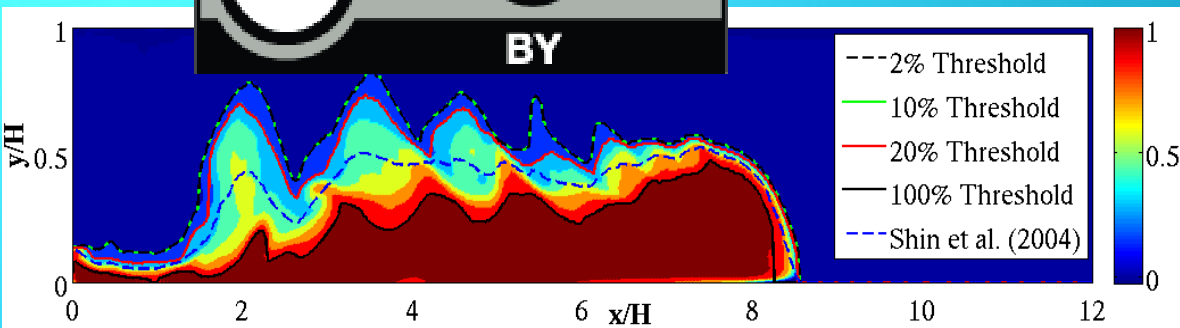
Immersed boundary method

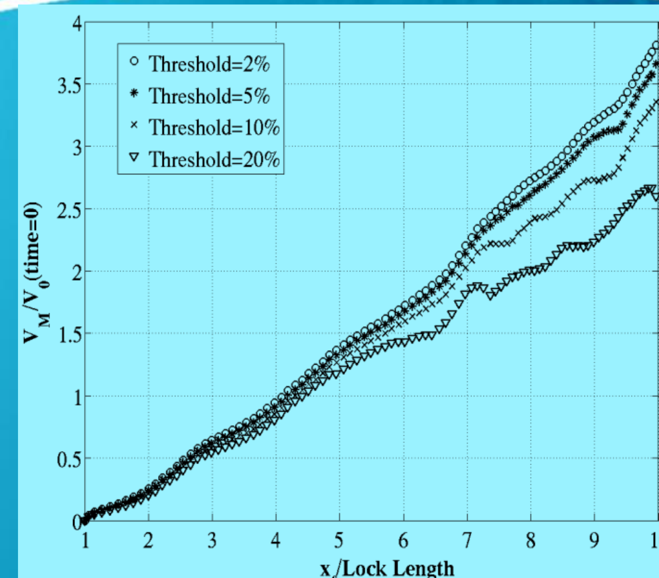
Boussinesq approximation – 4th order velocity-vorticity form of N-S.

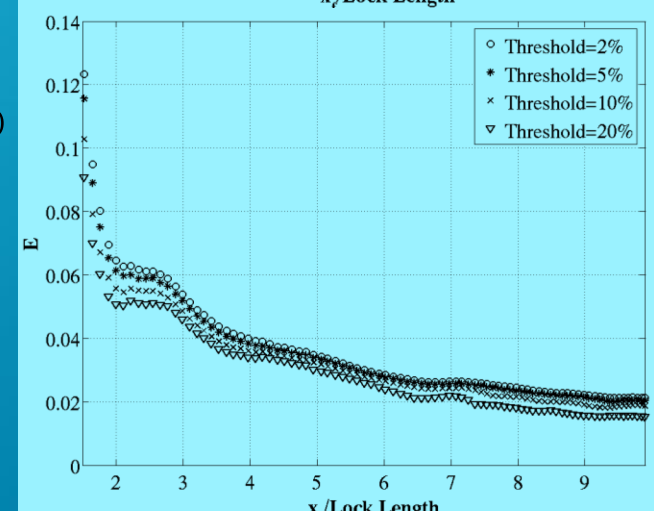
4th order compact-finite difference, Runge-Kutta

(Bhaganagar, JHR, 2014)

Calculation of Entrainment: Numerical Challenges





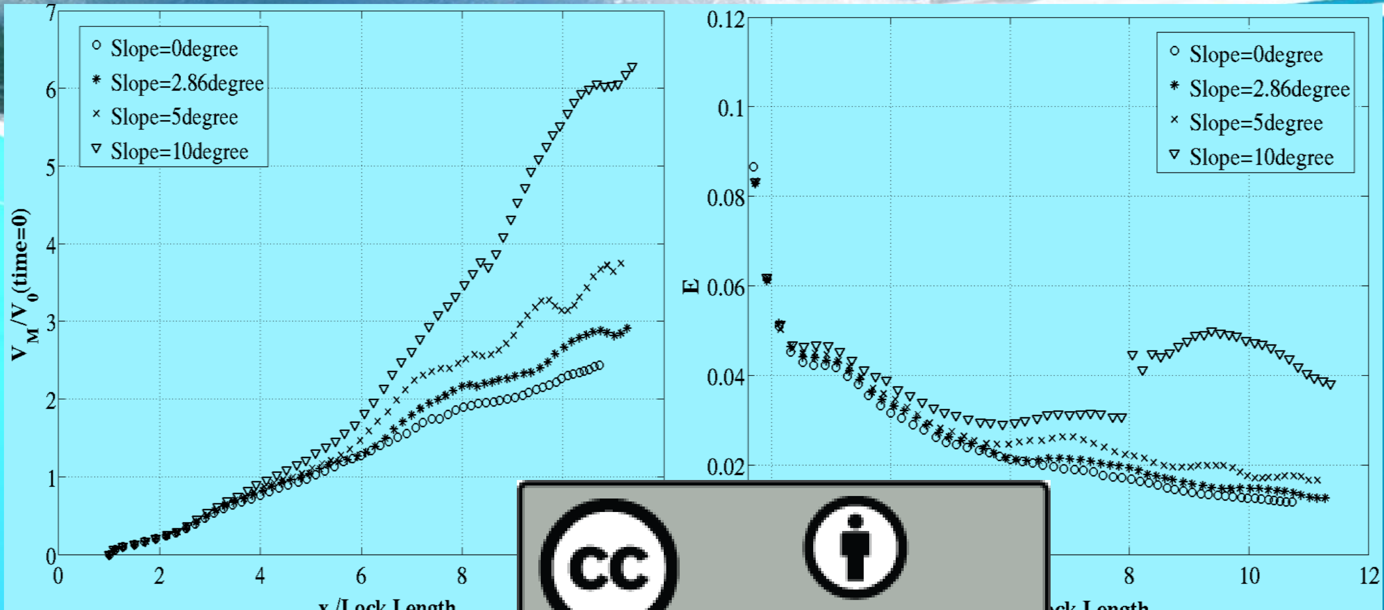


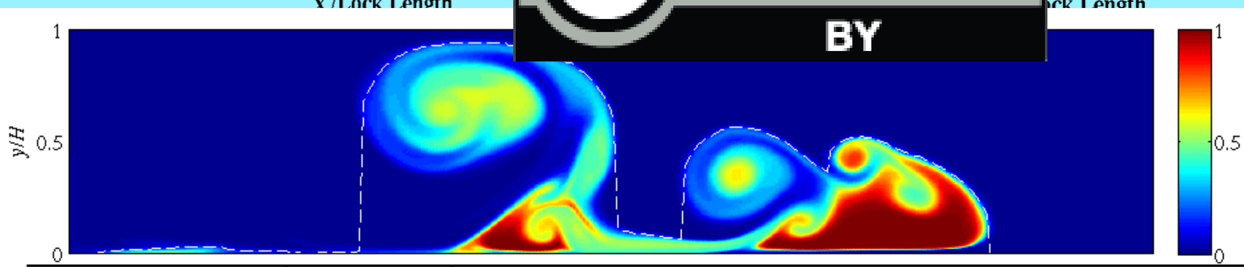
Identify the interface of mixed and ambient fluids to obtain the current height profile ($h(x,t)$) employing density threshold.

Volume of mixed fluid is estimated by integrating the current height profile in streamwise direction from leading edge to tail of the current. Density threshold is the lowest density fluid that is originated due to the mixing in shear interface at the top of the dense current

$$E(t) = \frac{<V(t)> - <V(t_o)>}{(l)(u_f)(t)} \qquad V(t) = \int_{xo}^{xf} \overline{h(x,t)dx}$$

Lock-Exchange Flows 2-D Framework

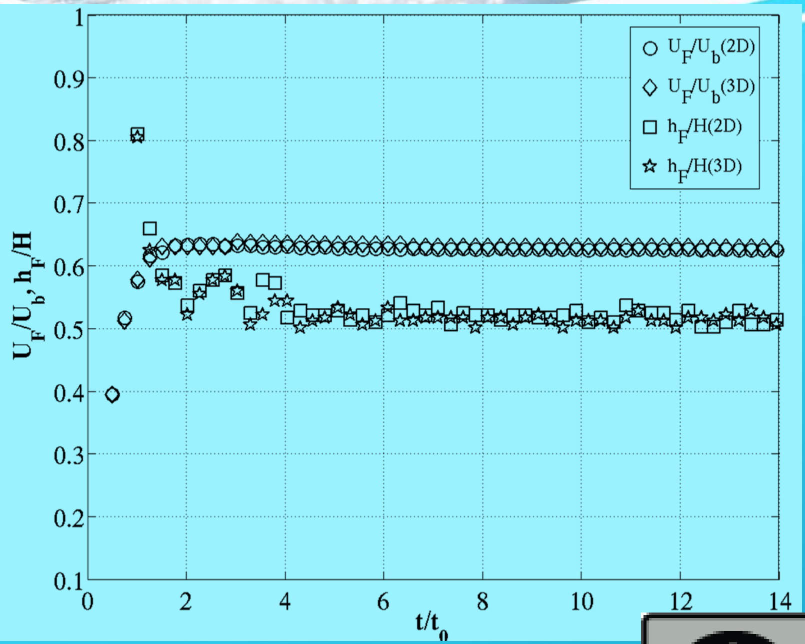


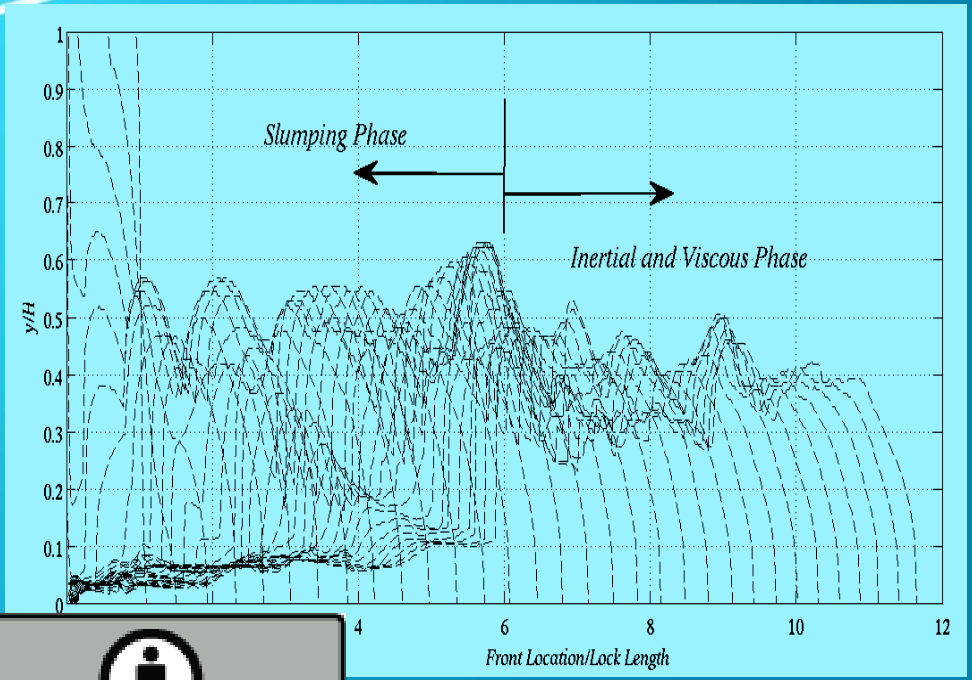


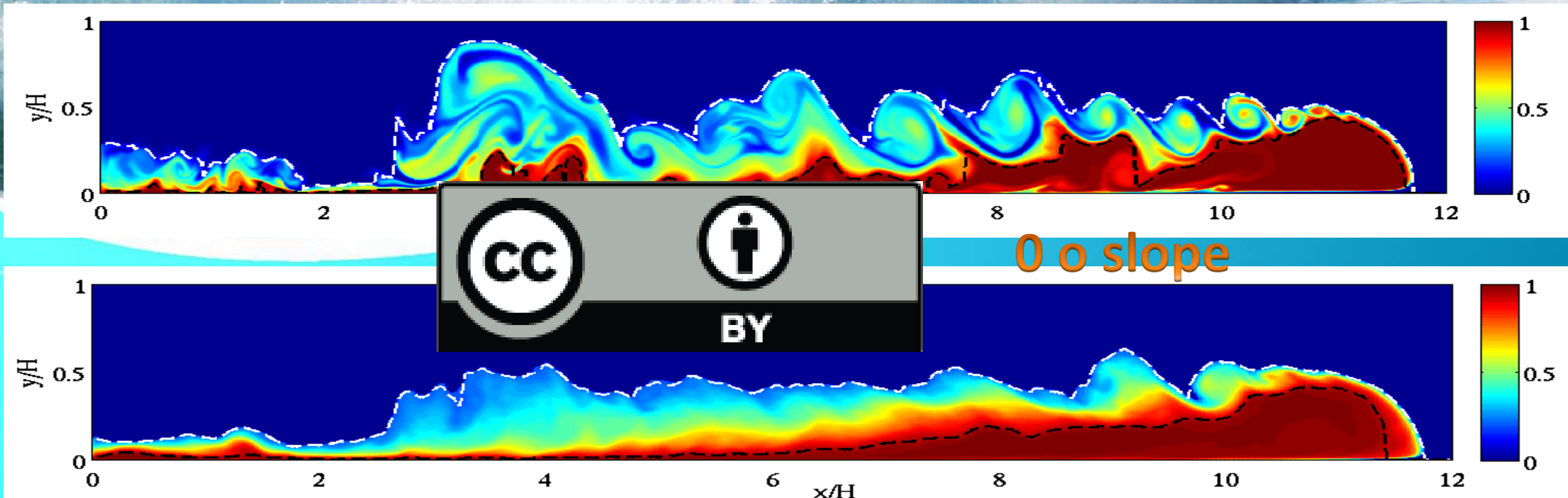
CASE	Slope(^{0})	$g'(m/s^2)$	$U_f(m/s)$	$U_b(m/s)$	Re_f	Fr	$AR(h/l)$
LELA	0	0.05	0.0455	0.0765	5293	0.595	0.33
LES5	5	0.05	0.0465	0.0773	5594	0.601	0.33
LES10	10	0.05	0.0475	0.0777	6043	0.611	0.33
LES20	20	0.05	0.0485	0.0785	6385	0.57	0.33

1. **Increasing slope enhances Re, E down the slope**
2. **K-H instabilities intensify unlike 3-D case**

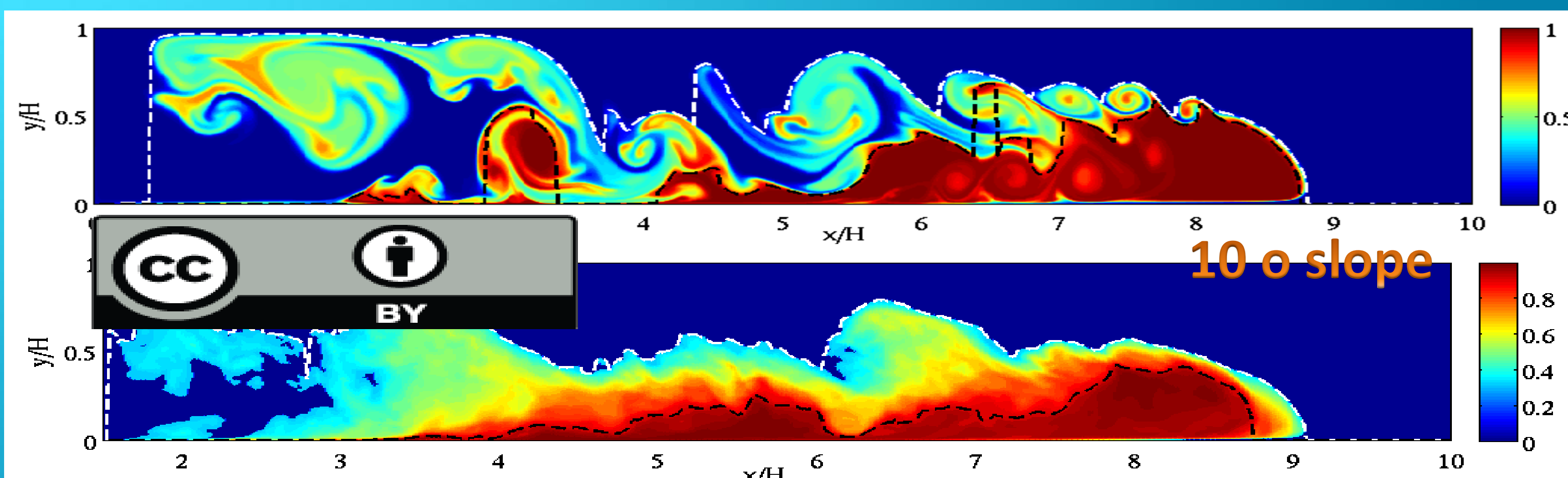
Lock-Exchange 3-D framework-



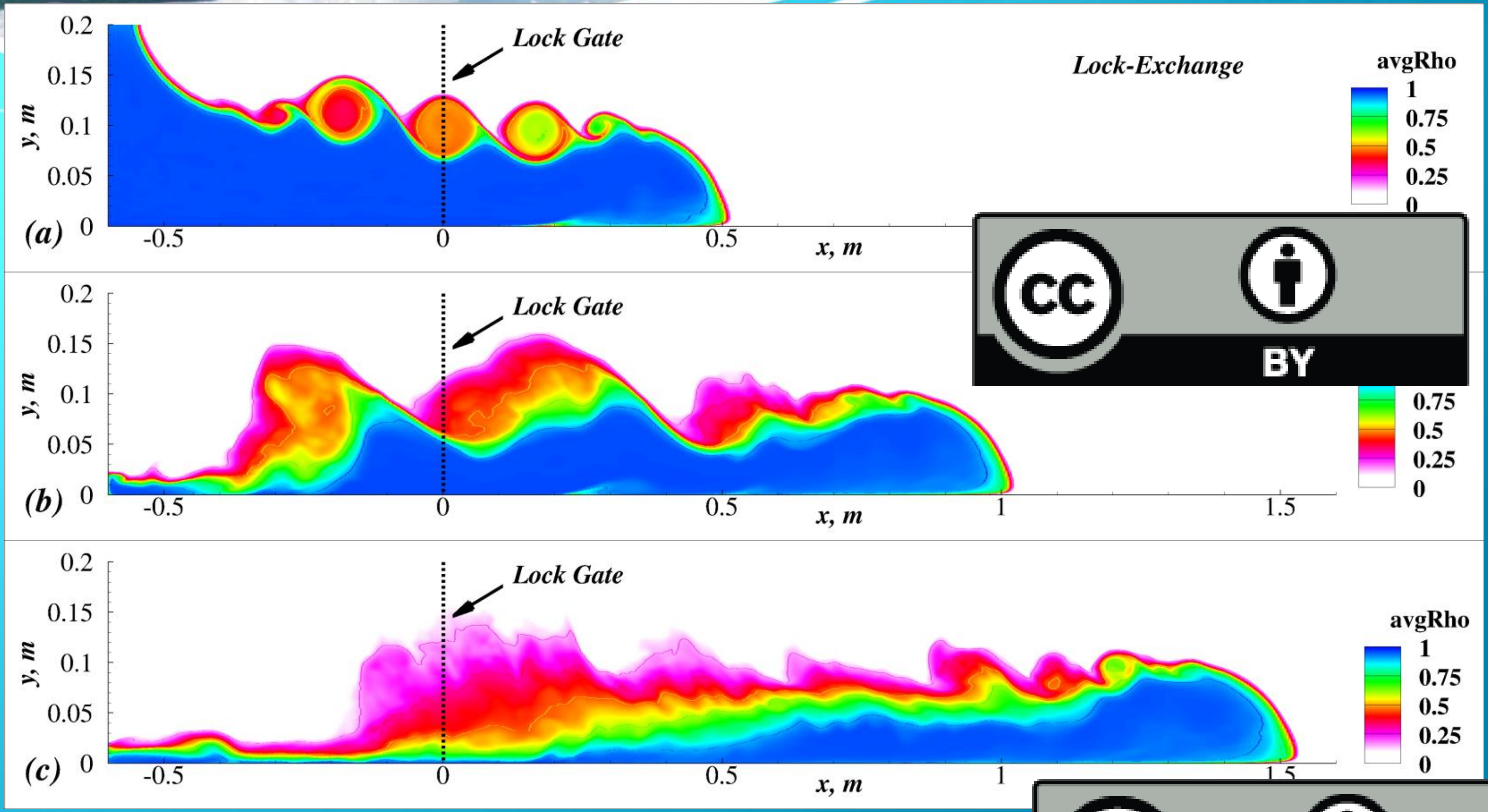


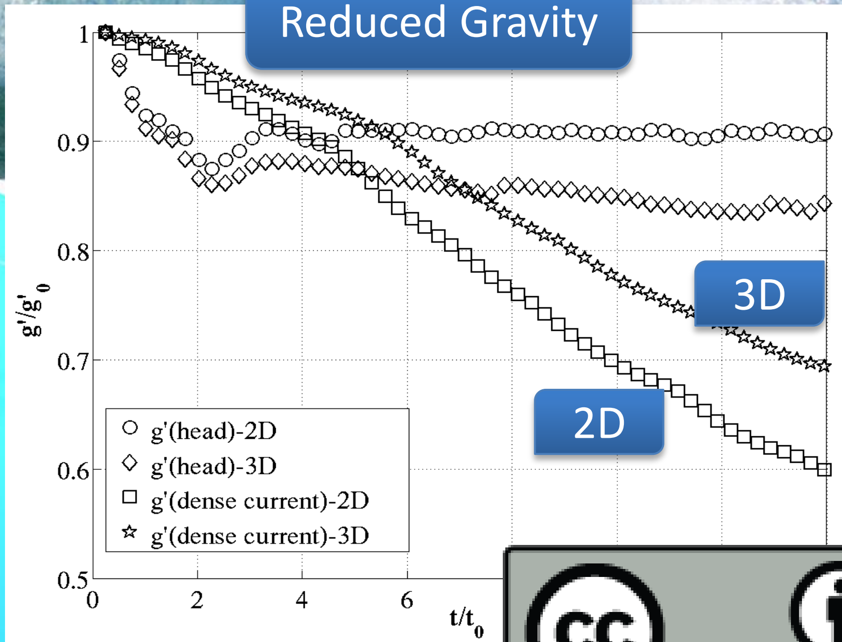


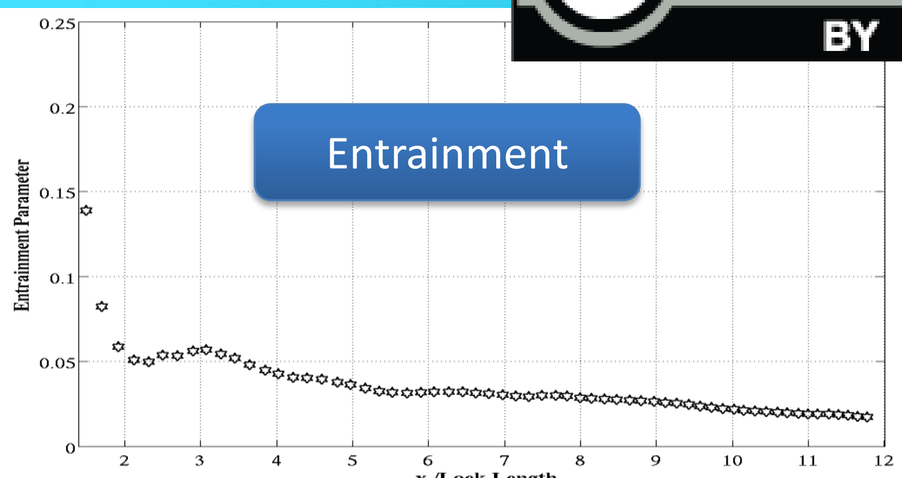
10 % density threshold (white dotted line) and original density fluid (black solid line) interface in (top) *2-D* Simulations; (bottom) *3-D* simulations for horizontal

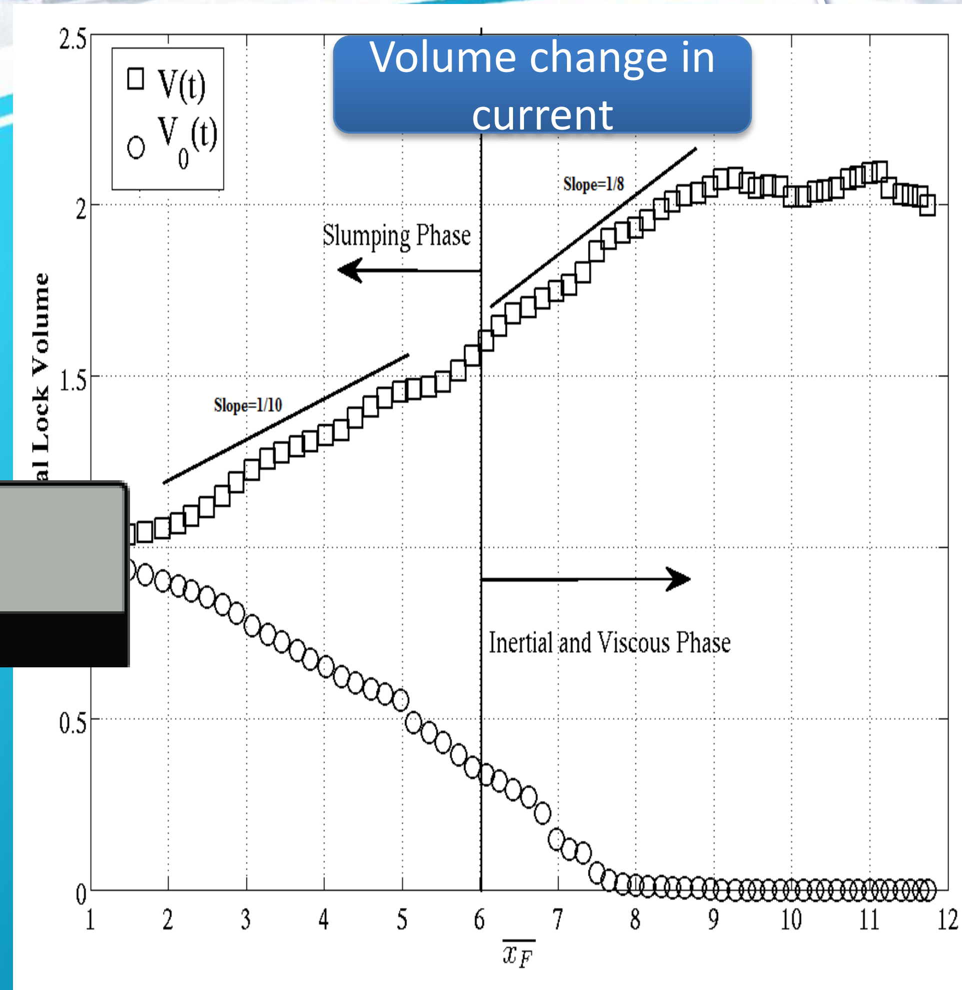


3-D Lock-Exchange Currents: Density Structures




Reduced Gravity
3D
2D
g'/g'$_0$
t/t$_0$
g'(head)-2D
g'(head)-3D
g'(dense current)-2D
g'(dense current)-3D
1
0.9
0.8
0.7
0.6
0.5
0
2
4
6


Entrainment
Entrainment Parameter
x$_f$/Lock Length
0.25
0.2
0.15
0.1
0.05
0
2
3
4
5
6
7
8
9
10
11
12


Volume change in current
V(t)
V$_0$(t)
Slumping Phase
Slope=1/10
Slope=1/8
Inertial and Viscous Phase
$\overline{x_F}$
2.5
2
1.5
0.5
0
1
2
3
4
5
6
7
8
9
10
11
12

3-D Lock Exchange Energetics

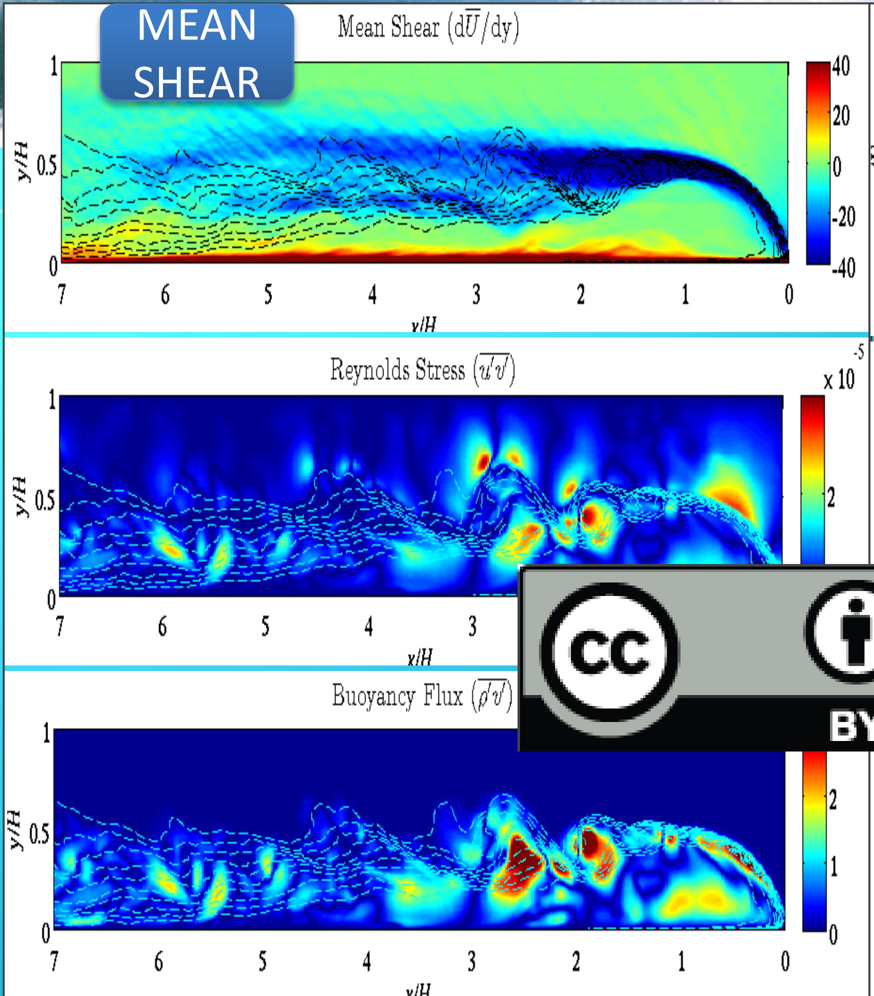


Figure 1. Energetics in slumping phase in reference frame overlaid by density contour (black dotted line) (a) mean shear, (b) Reynold Stress, (c) Buoyancy Flux

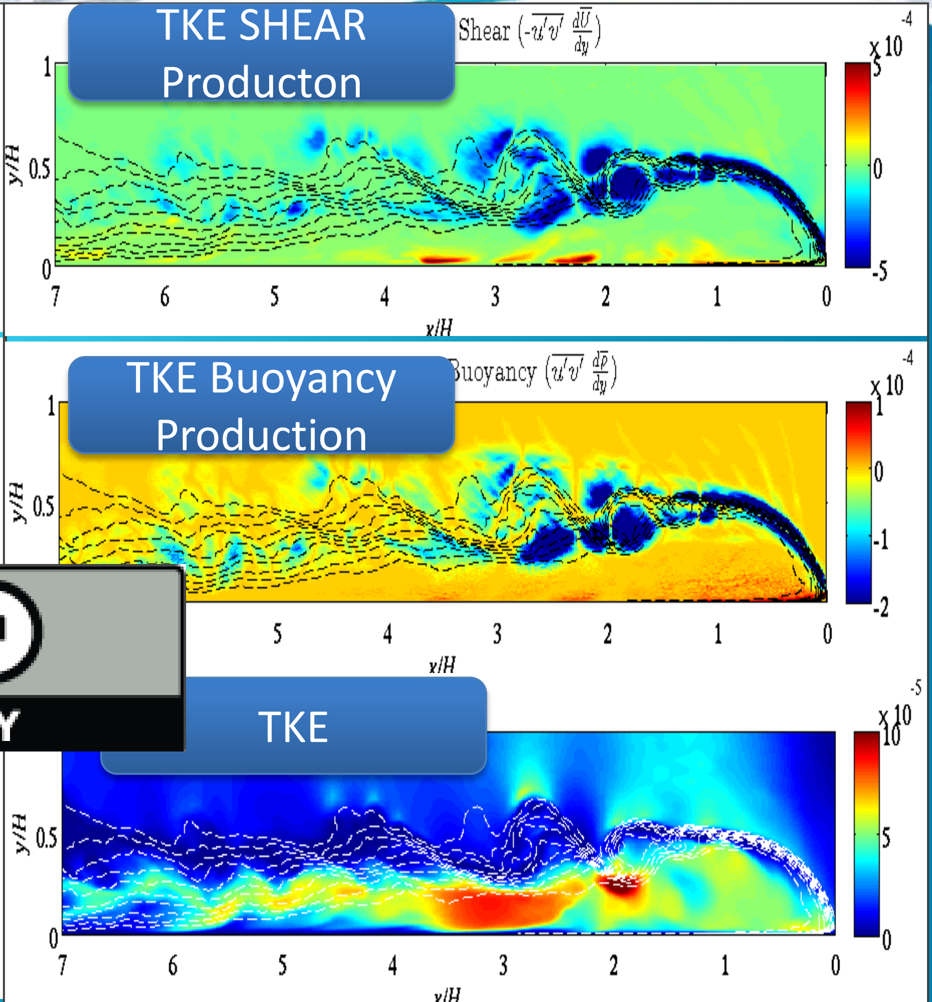
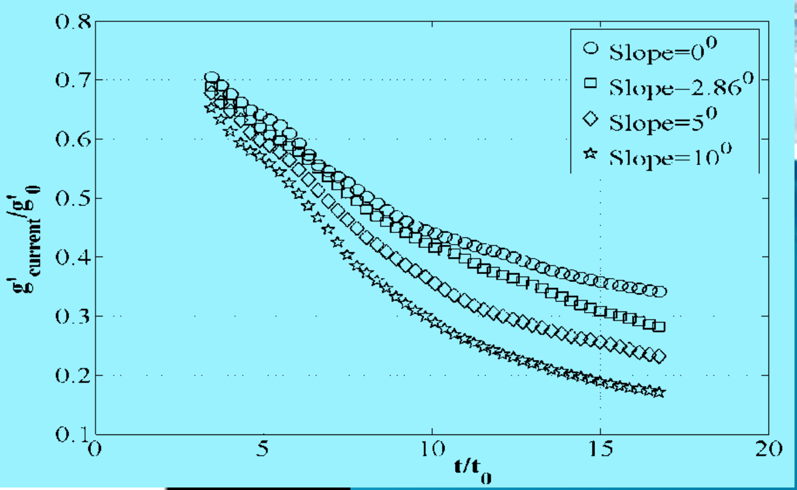
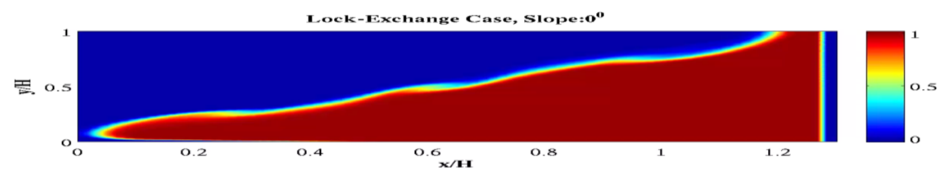
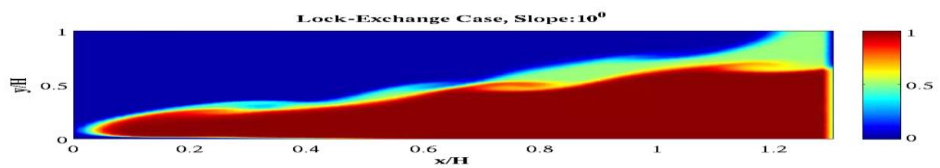


Figure 1. Energetics in slumping phase in reference frame overlaid by density contour (black dotted line) (a) TKE production from shear, (b) TKE production from buoyancy, (c) TKE

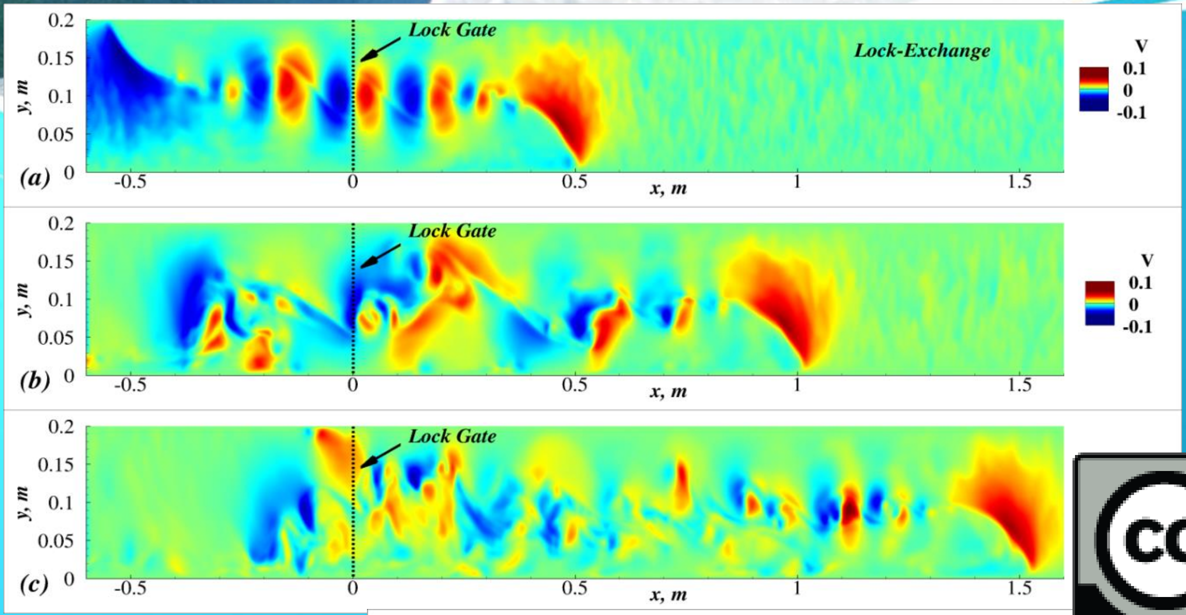
EFFECT of SLOPE on 3-D Lock Exchange CURRENTS

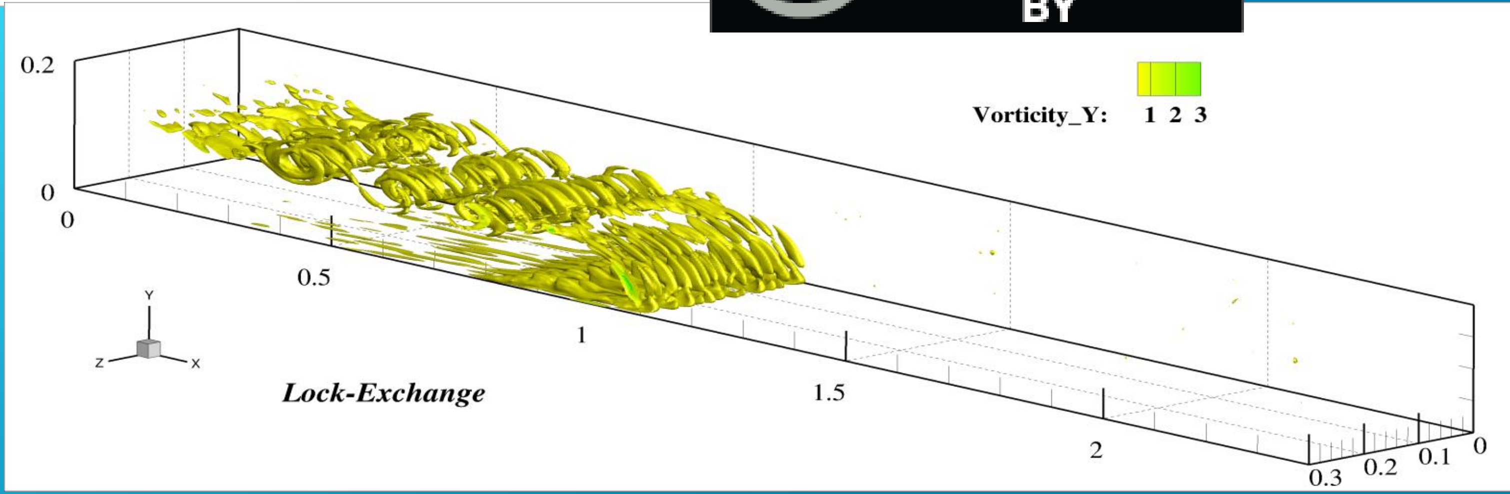




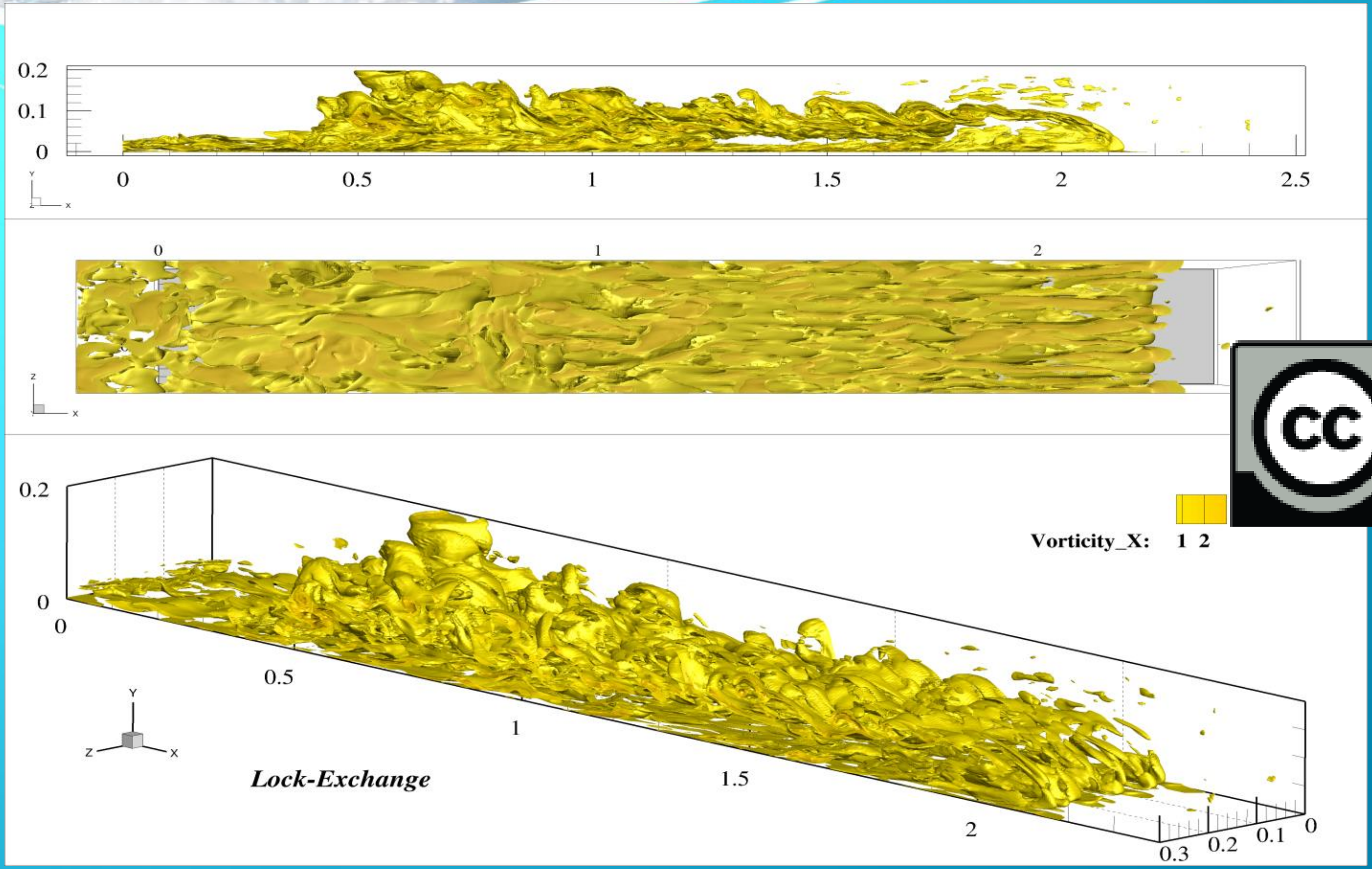


Turbulence Structures in 3-D Lock Exchange Flows

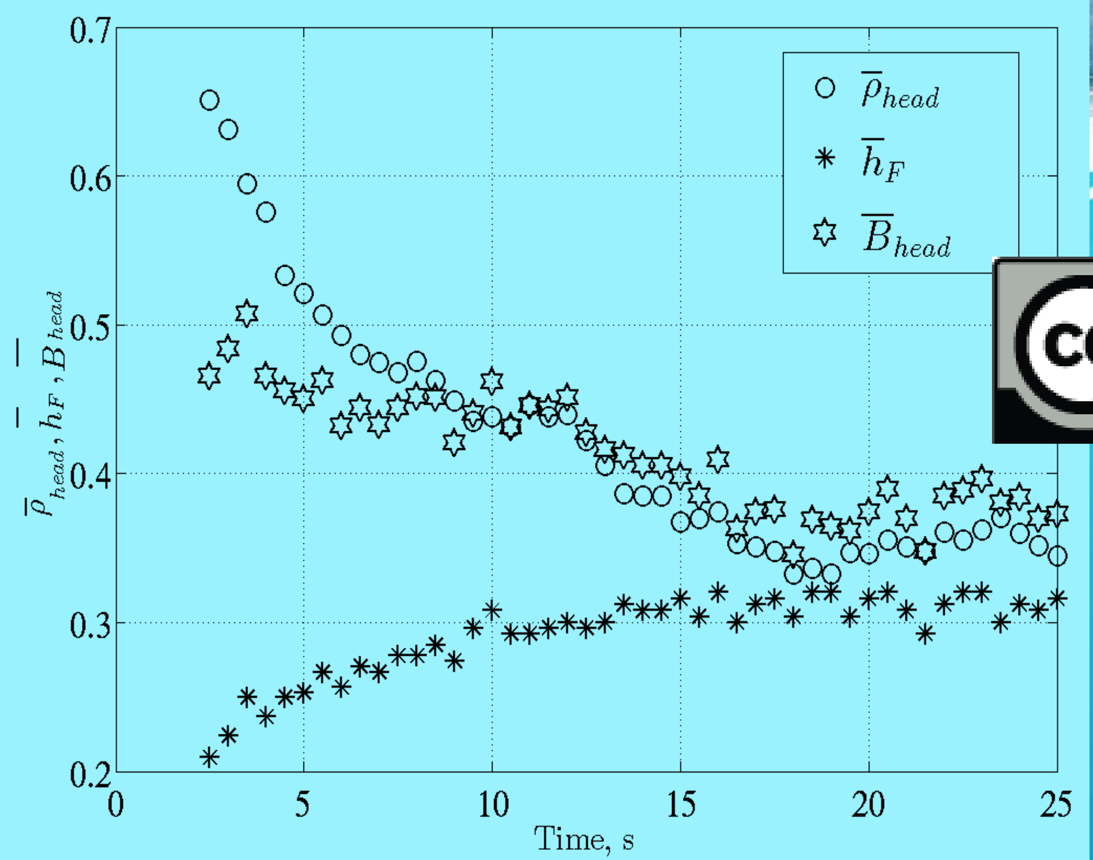




Evolution of Vorticity Fields in 3-D Lock Exchange Flows



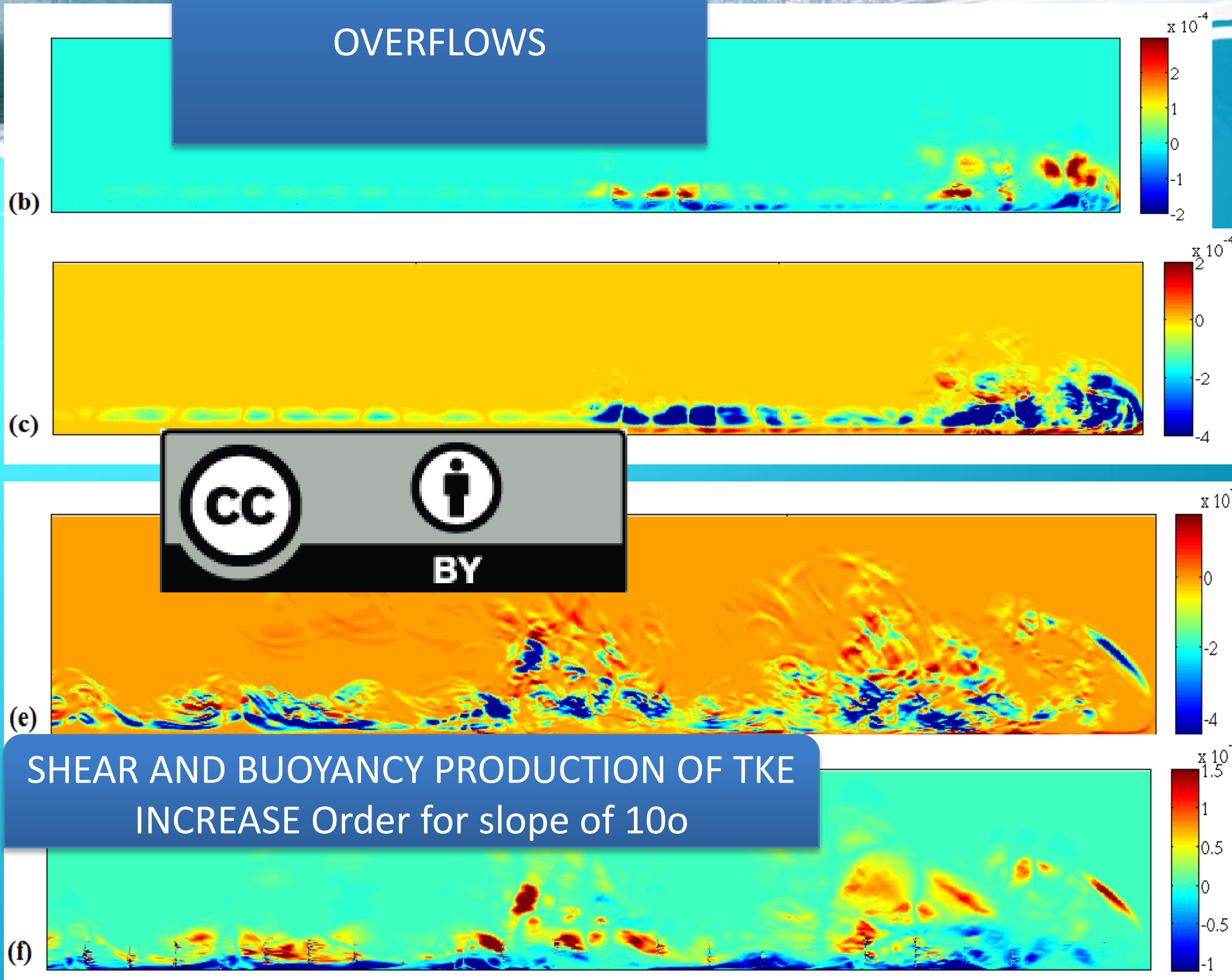
3-D Overflows



	Slope	*g'(m/s²)*	*U_f(m/s)*	*U_b (m/s)*	*Re_f*	*Fr*	*U_q(m/s)*	*AR(h/l)*
CFH	0	0.45	0.0455	0.1	5712	0.455	0.1	NA
CFS5	5	0.45	0.053	0.1224	8816	0.432	0.1	NA
CFS10	10	0.45	0.06	0.141	13960	0.424	0.1	NA
CFS20	20	0.45	0.064	0.1732	21925	0.369	0.1	NA

Front speed is proportional to cube root of the buoyancy flux $(g_o^{'}Q)^{1/3}$ for dense currents over slopes and it depends on the Reynolds number.

OVERFLOWS

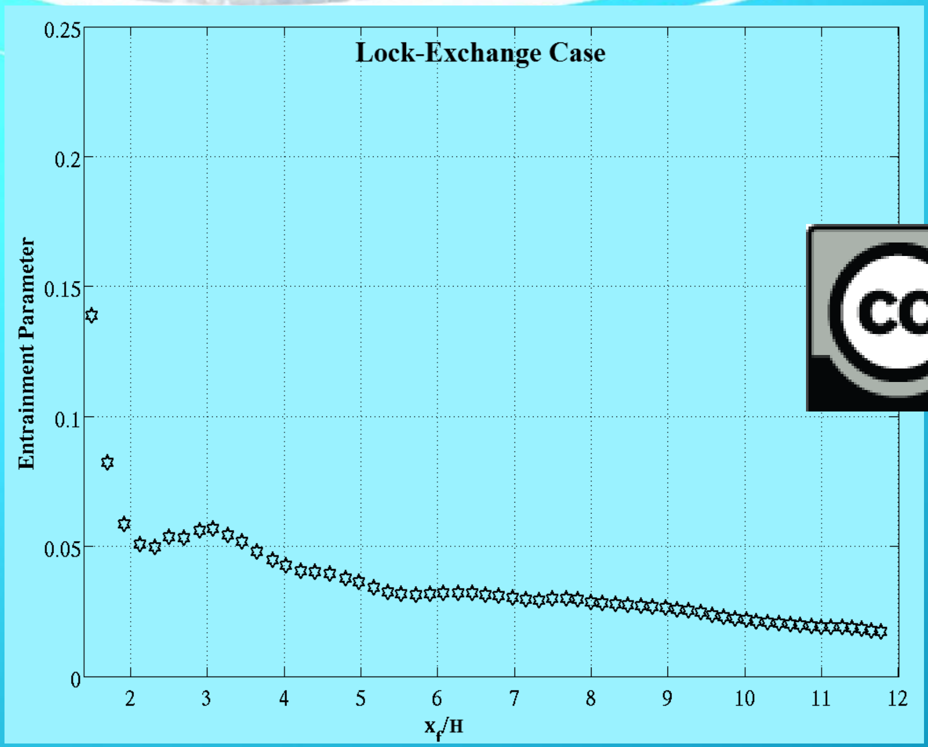


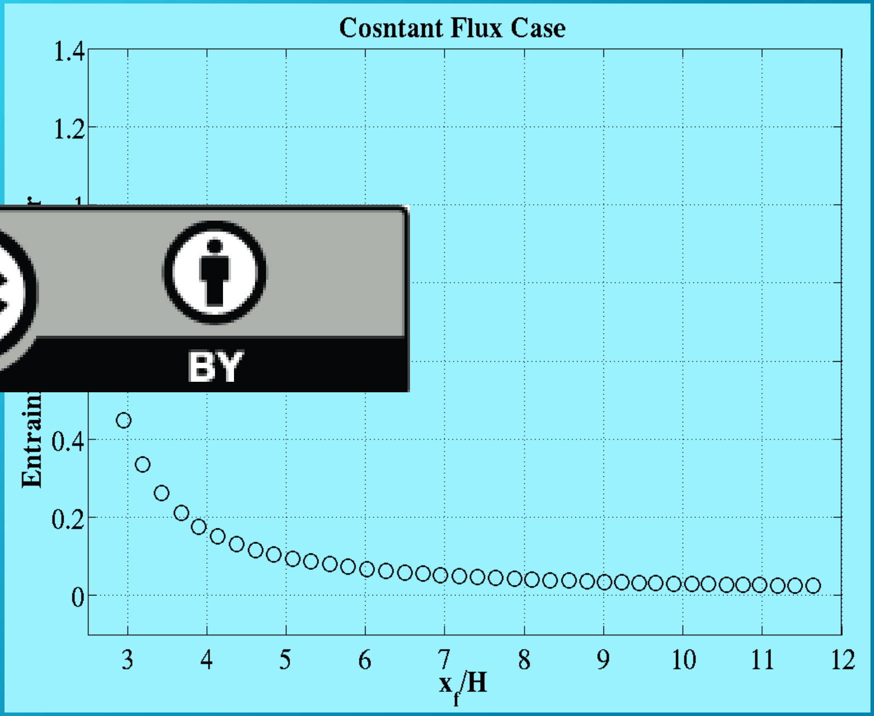
Slope =0
(top) shear production
(lower) buoyancy production

Slope =10 o
Shear Production
Buoyancy production of TKE

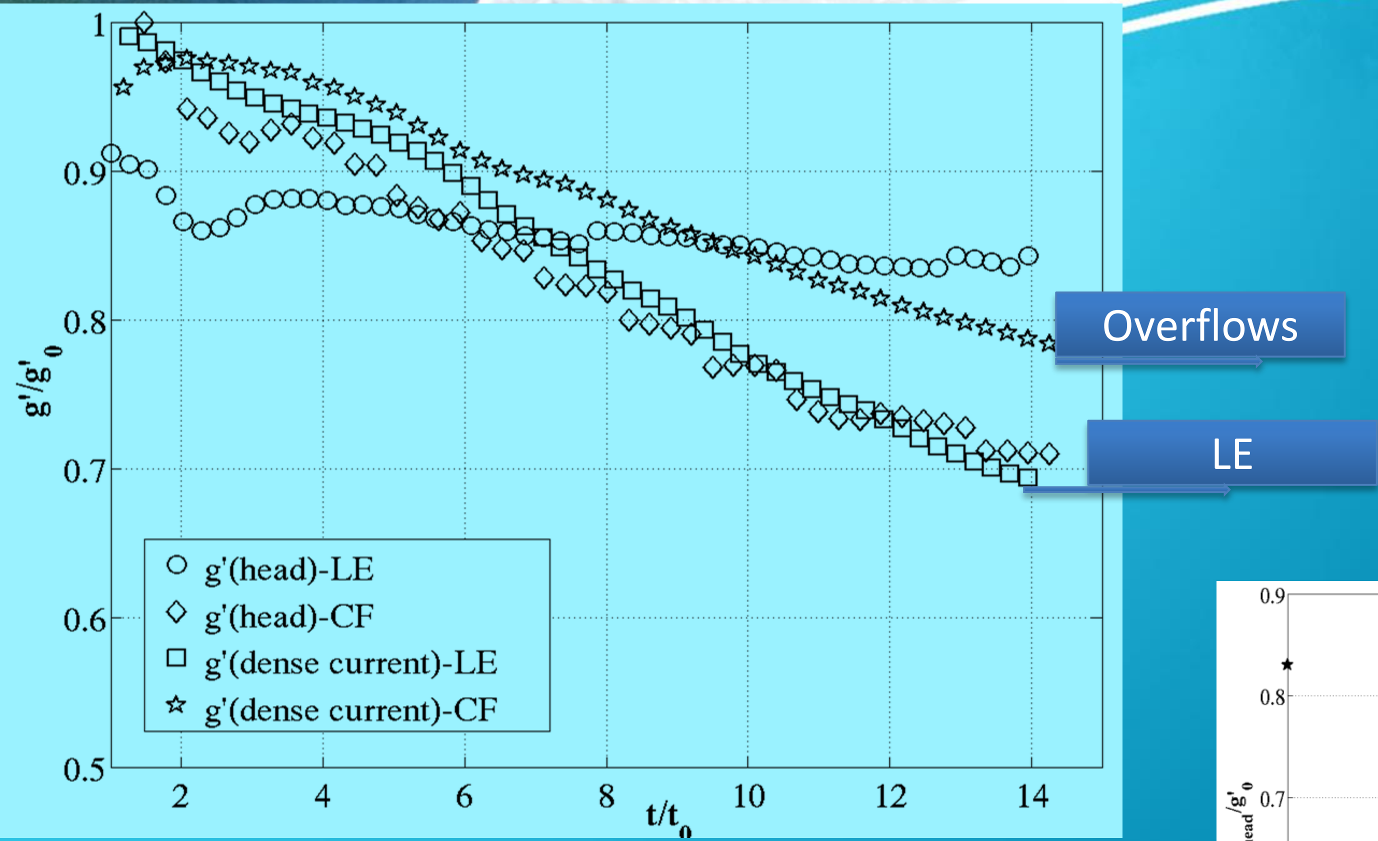
SHEAR AND BUOYANCY PRODUCTION OF TKE INCREASE Order for slope of 10o

Entrainment between L-E and Overflows

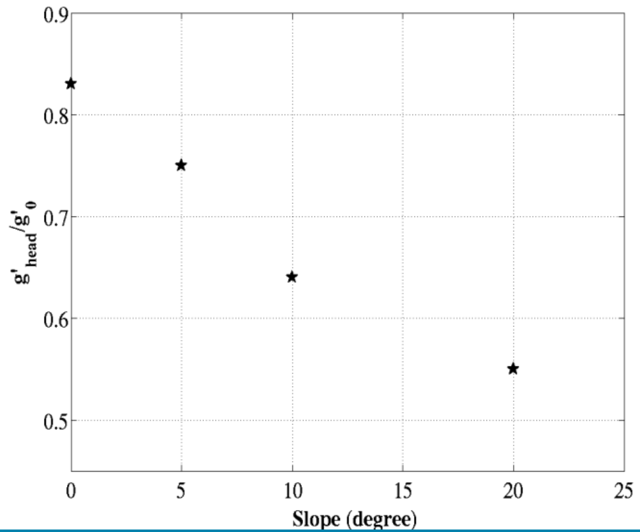




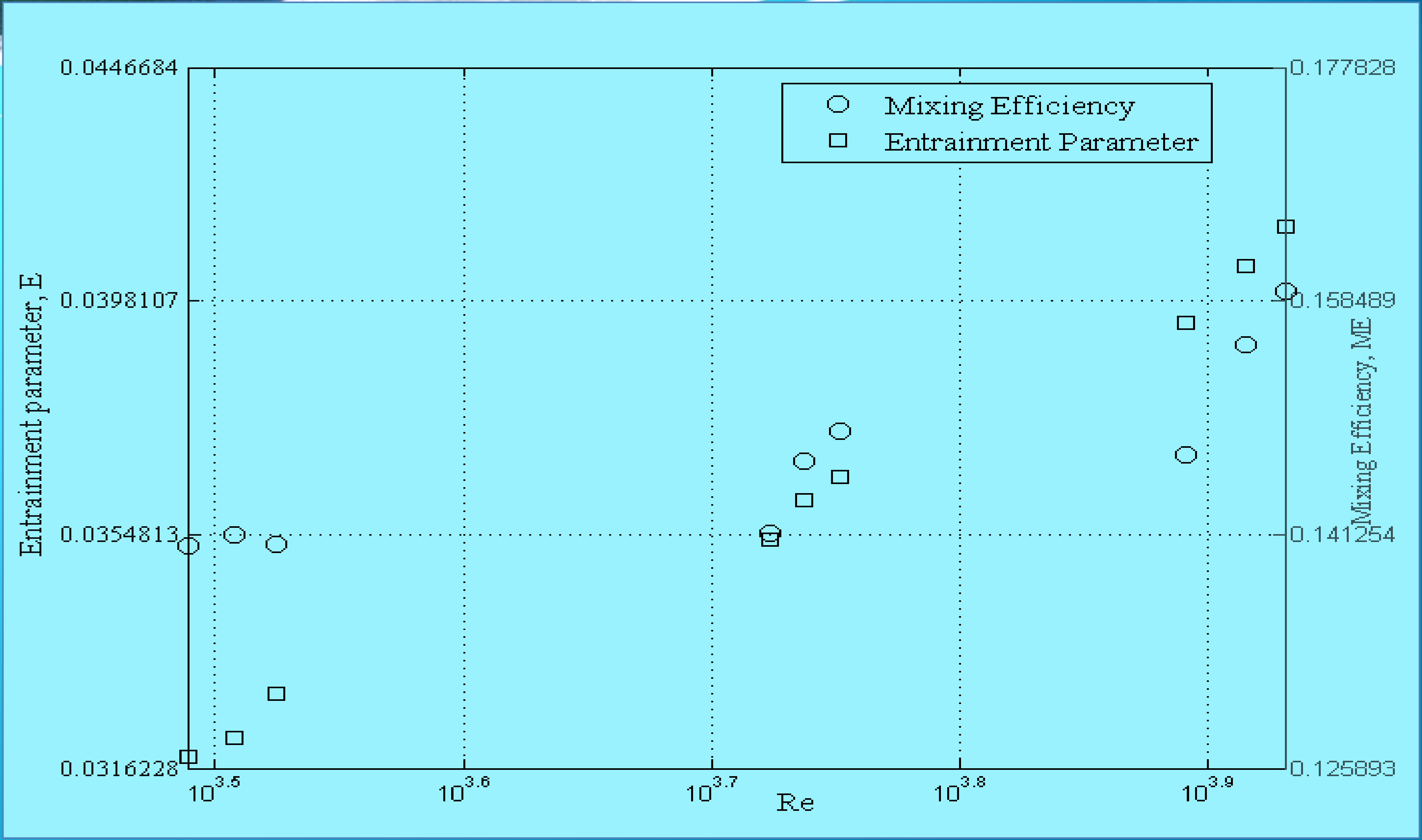
Mixing of Lock-Exchange Flows vs. Overflows



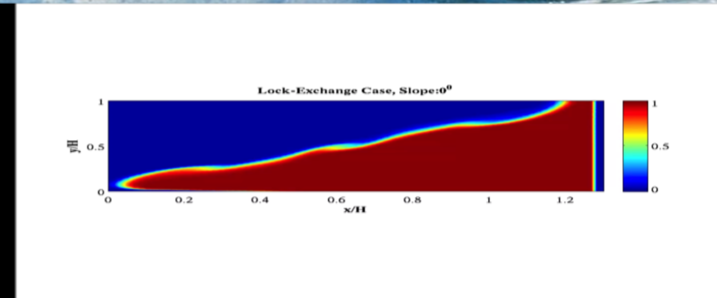
OVERFLOWS: INCREASING SLOPE increases DILUTION AT HEAD



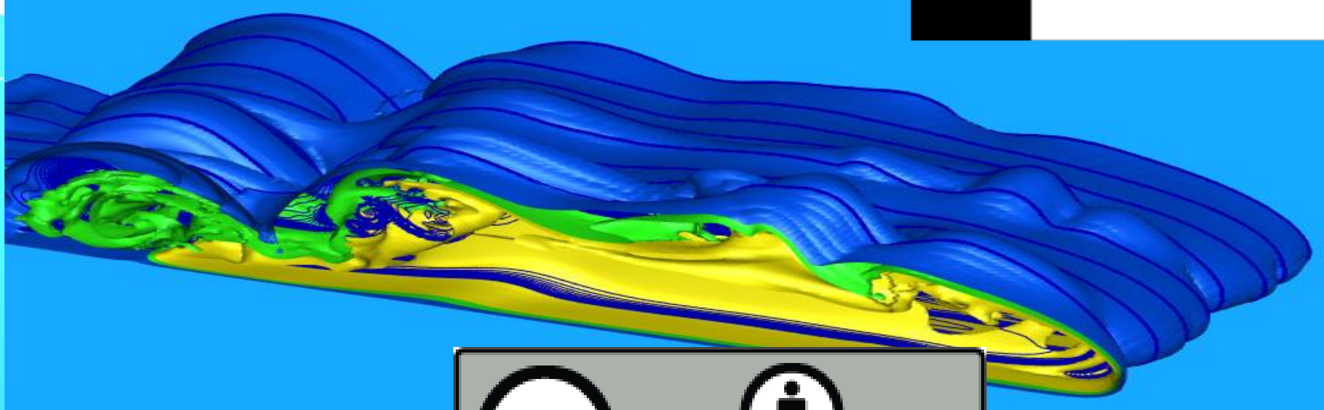
ENTRAINMENT PARAMETER & MIXING EFFICIENCY vs. Re

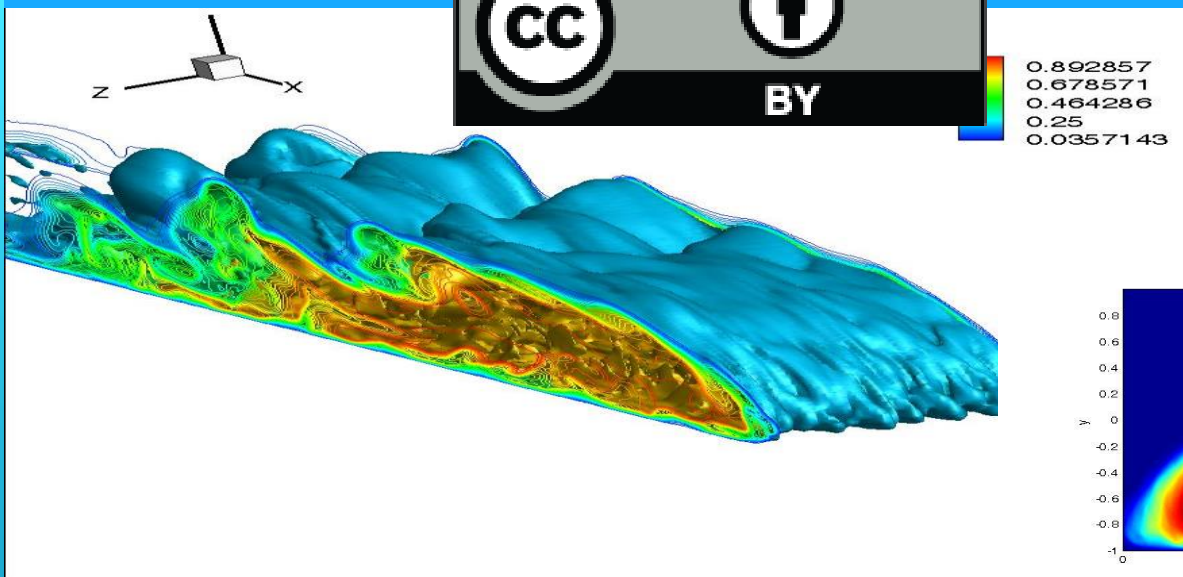


ROUGHNESS ENHANCES MIXING

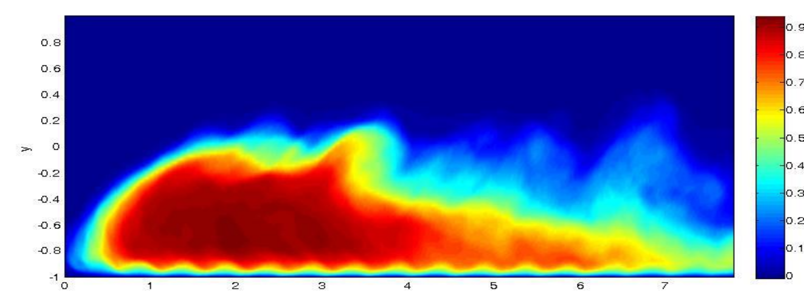


SMOOTH





ROUGH



CONCLUSIONS

- DNS/LES of L-E, overflows over sloping surfaces performed for lab-range of Re.
- Calculation of E: threshold, front location.
- Shear and buoyancy production play role in TKE generation for L-E and Overflows over slope -> parameterization needs to be based on TKE production
- Reduced gravity in current vs. head - Overflows and L-E exhibit differences
- L-E entrain higher than overflows due to enhanced K-H instabilities.
- Roughness enhances entrainment quite significantly beyond head region.

Acknowledgements

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Dr. Claudia Cenedese collaborator and teaching valuable lessons on entrainment and density currents.

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