THE CUMULUS CLOUD AS A TRANSIENT DIABATIC PLUME

RODDAM NARASIMHA
Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore

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INTROSPECT 2017 (International Workshop on Representation of Physical Processes in Weather and Climate Models) IITM, Pune

CLIMATE SCIENCE

Physicists, your planet needs you

Climatologists highlight cloud mysteries in an attempt to lure physicists to their field.

BY QUIRIN SCHIERMEIER

Nature Vol. 520, 9 April 2015

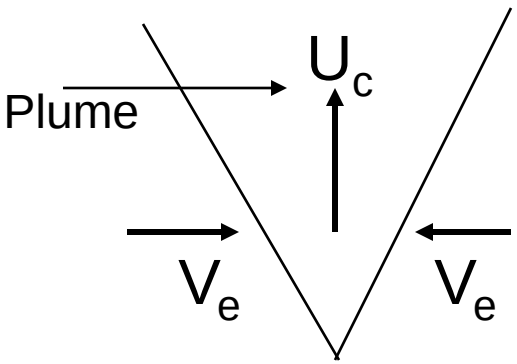
BACKGROUND 1

- Clouds are complex flows involving multiple phases, thermodynamics, microphysics, radiation . . . ? ?

- A central problem in the fluid dynamics of clouds concerns their interaction with the ambient dry air, in particular through entrainment, which is also **associated with the dynamic behind shape**

- Taylor's entrainment hypothesis for free turbulent shear flows (Taylor 1945, Morton, Taylor, Turner 1956):
  entrainment velocity $V_e \propto$ characteristic mean velocity U_c
  Later refinements: replace U_c by u'_c, $(u' w')^{1/2}$ etc.

- Often works well for plumes (Turner 1973, 1986 JFM)



BACKGROUND 2

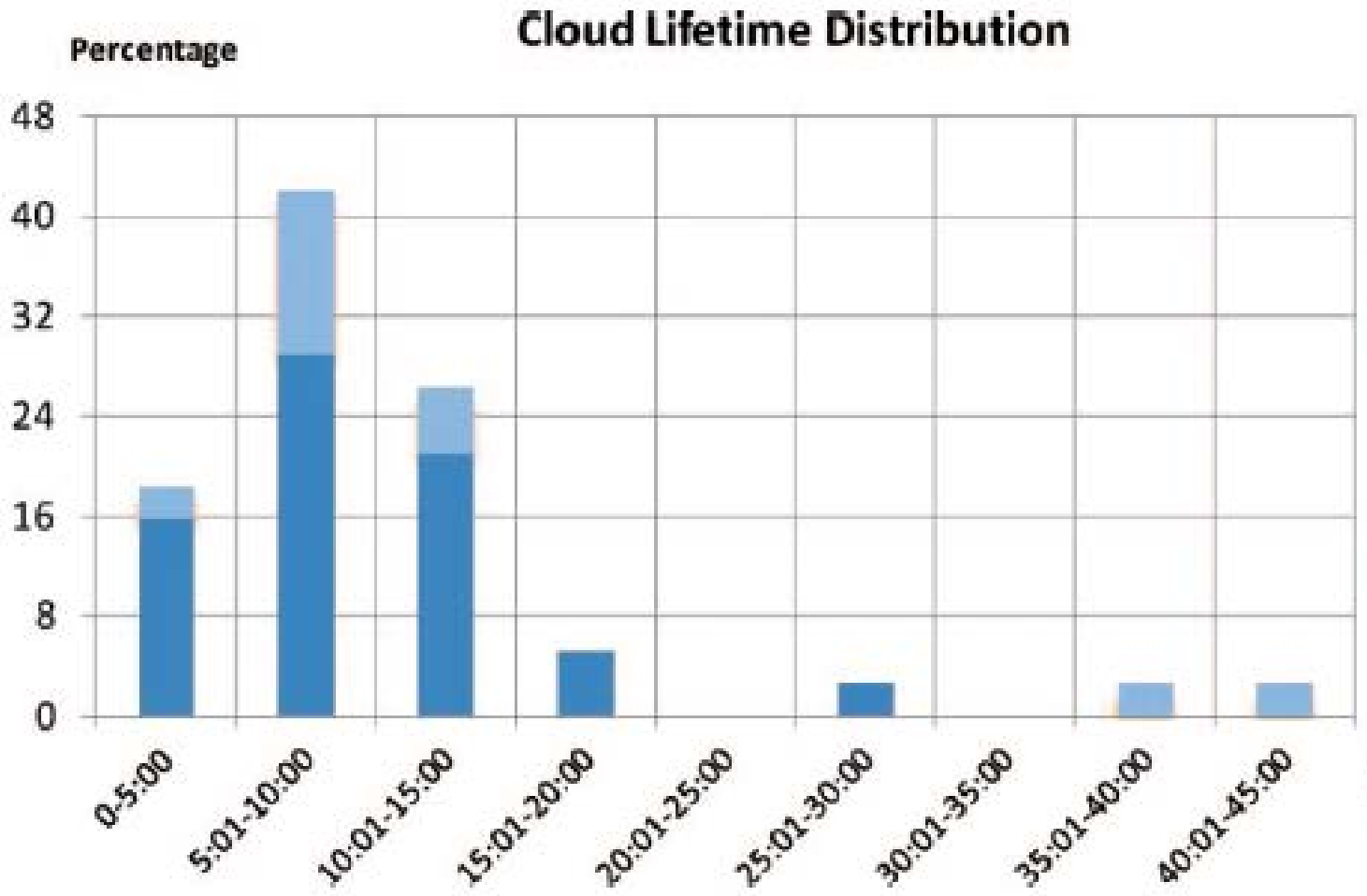
- Does not work for cumulus clouds – heaps, (the hot cumulus) towers of Riehl (1958), **not fans or cones**

- Telford (1975):
  Liquid water content remarkably constant across cloud, decreases monotonically from cloud base
  ➡ "The problem of explaining infinite horizontal diffusion and zero vertical diffusion"

- Or (from present work on momentum) the other way round?

- Emanuel (1994):
  "Early cloud parameterization schemes based on the **similarity** plume model . . . [were] thoroughly discredited by observations".

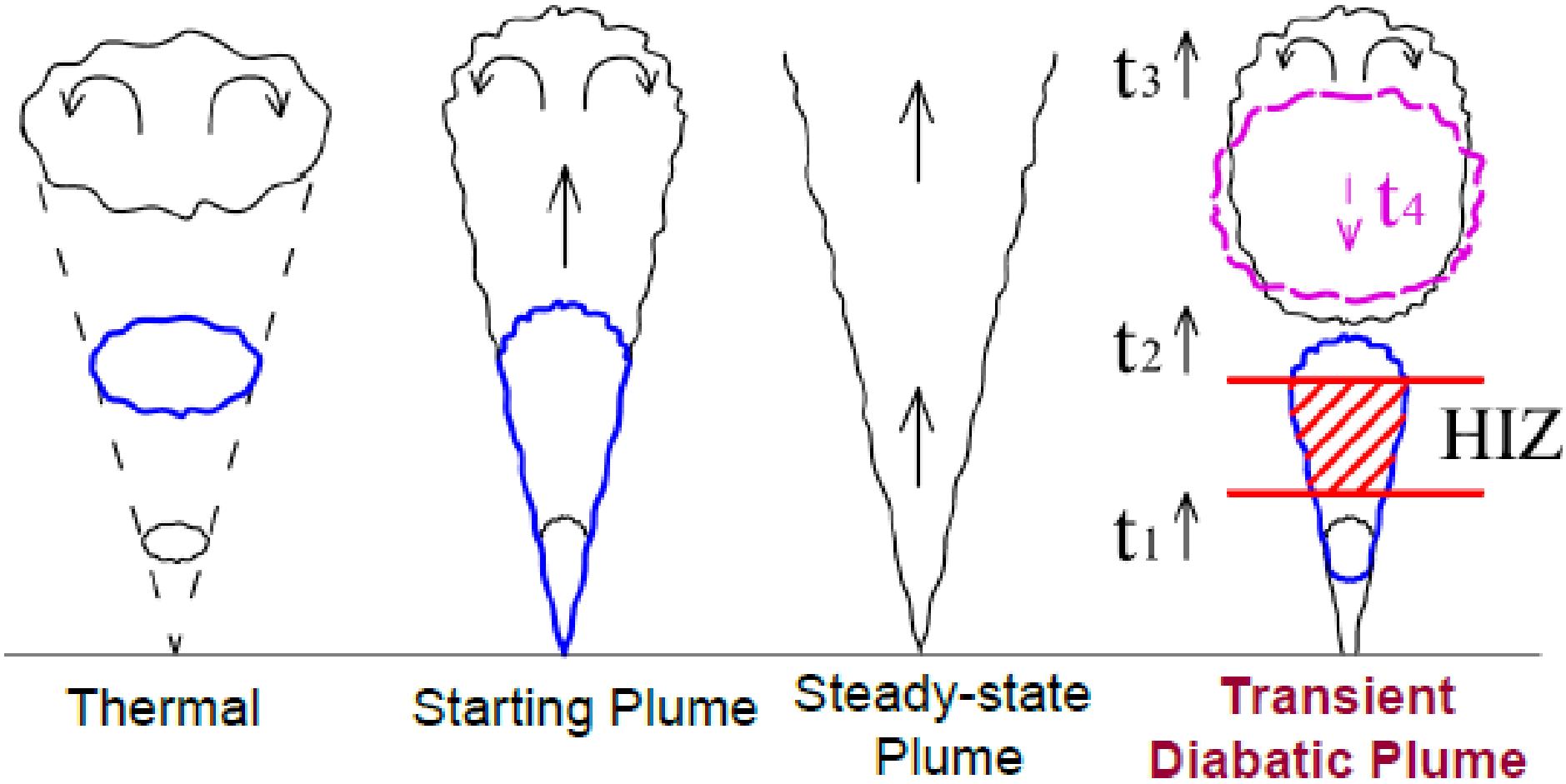
CLOUD LIFETIMES



Total number of clouds in the population- 38

Mean- 10:30 min
Median- 8:00 min

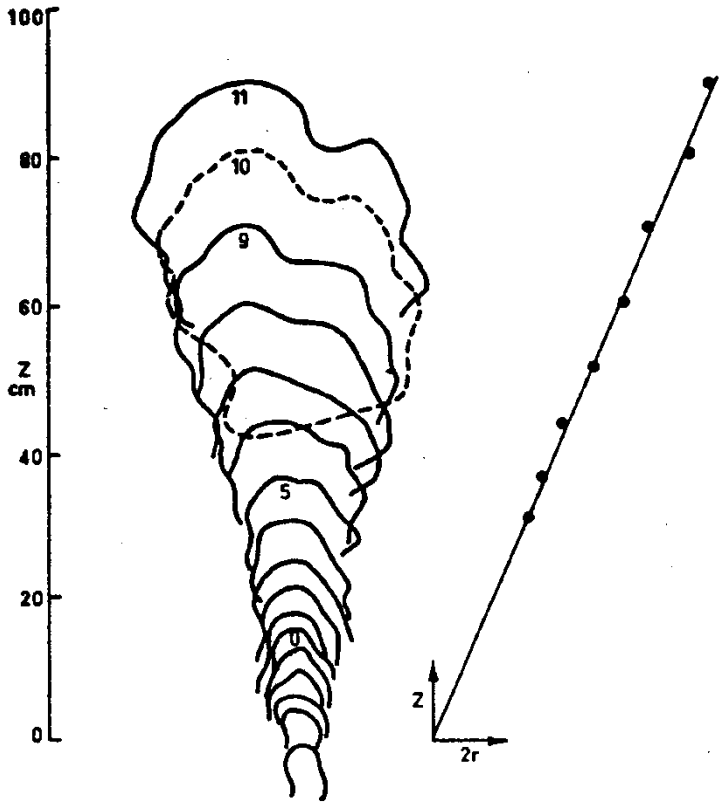
PHYSICAL FLOW MODELS



Turner 1973, introduced again

RN+ 2011 PNAS

MODELLING CLOUDS

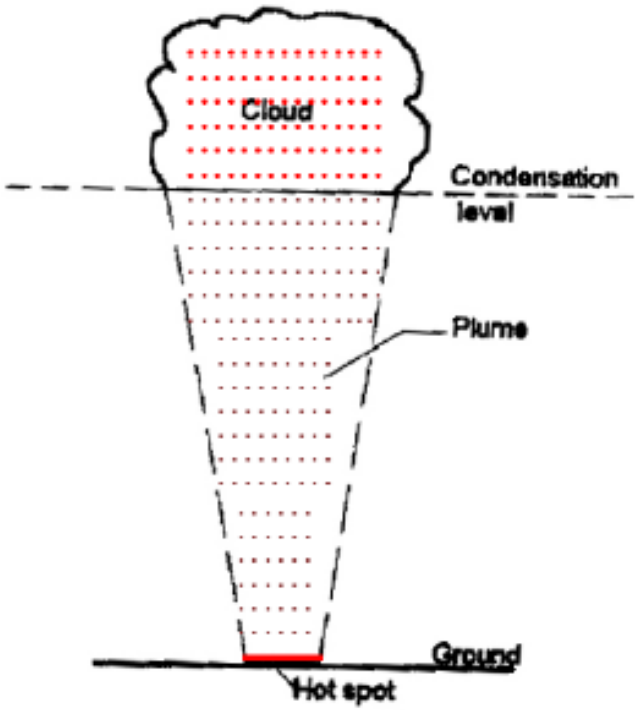


. . . large convective clouds . . . which are not adequately described by similarity theory but for which there is at present no alternative model.

J S Turner 1973 Buoyancy Effects in Fluids

Simulation of cumulus clouds in laboratory

Principle



1. Physical model:

   Transient turbulent plume/jet of a single-phase *'cloud fluid'*, with off-source addition of heat to simulate latent heat release due to condensation in natural cumulus clouds

2. We work with *water, not moist air.*

3. Shape primarily determined by *large-scale* entrainment processes.

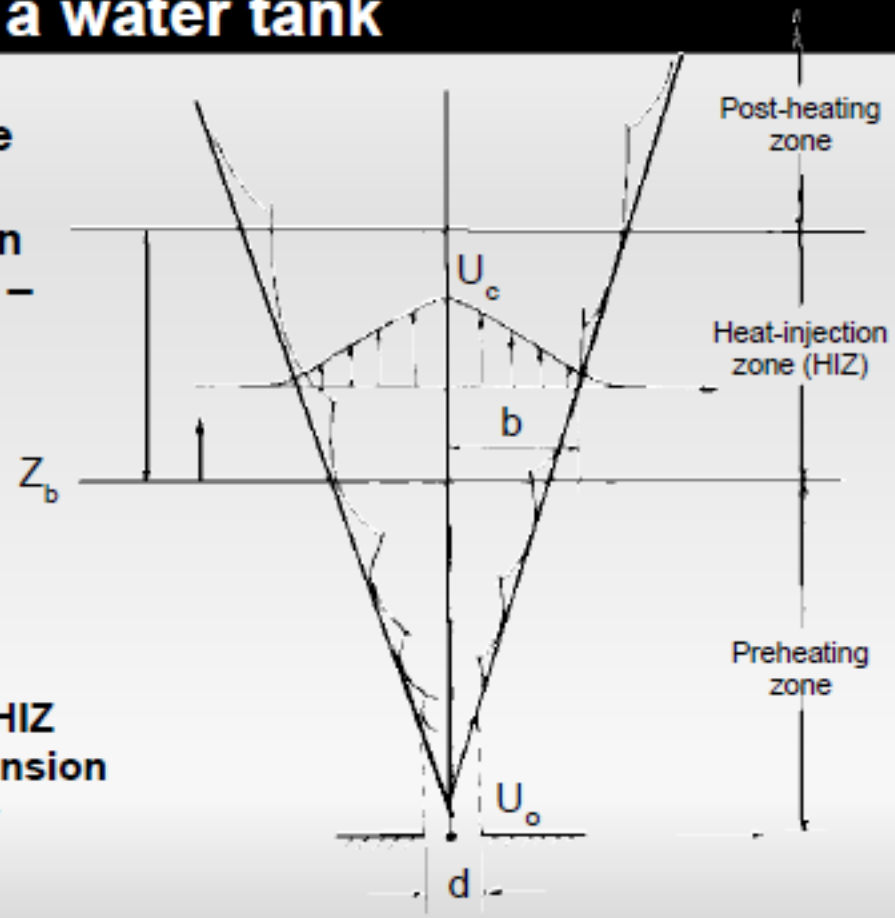
Recent work shows (Narasimha *et al.*, PNAS, 2011)
"Clouds are ***transient diabatic*** plumes"

Dynamical similarity: Cloud-like flows in a water tank

Non-dimensional heat release number (analogous to bulk Richardson number) has been proposed (Bhat & Narasimha – 1996 JFM).

$$G = \frac{\alpha g}{\rho c_p} \frac{z_b^2}{d^3} \frac{Q}{U_0^3}$$

Q = Total heat input rate in the HIZ
α = Co-efficient of thermal expansion
ρ = Water density; g = gravity
C_p = Heat capacity of water



Dynamical similarity: Cloud-like flows in a water tank

Flow	Width b (m)	Centre-line velocity U (m/s)	G' = $\frac{\alpha g}{\rho c_p}\frac{Q}{b_b U_b^3}$
Cumulus	500	3 - 4	0.11 - 0.53
Cumulonimbus	1200 - 2500	10 - 25	0.14 - 0.46
Jet/Plume d = 4 mm, z/d = 50, Q = 600 W	21 x 10^{-3}	38 x 10^{-3}	0.25

Venkatakrishnan *et al.* – 1998 Current Science

Re in the experiments is much lower, but jets and plumes are relatively insensitive to *Re*, for *Re* > 10^3 - 10^4

Dynamical similarity: Cloud-like flows in a water tank

- Heat release into the cloud fluid:

  ~ 1 W/m^3 in the atmosphere

- What matters: The ratio *G*

  ~ (Heat release) / (Energy flux)

- To get same value of *G* in a water tank as in clouds, we need heat release of O(1 kW) in 5 cm x 5 cm x 10 cm = 250 cm^3 = 250 x 10^{-6} m^3.

- This idea forms the basis for design of the off-source heating mechanism.

(Narasimha 2008)

Non-Dimensional heat release parameter: Bulk Richardson No.

$$G = \frac{\beta g}{\rho C_p}\frac{Q}{bU^3} \sim \frac{heating\ rate}{kinetic\ energy} \quad \text{for jets}$$

$$\sim \frac{heating\ rate}{buoyancy\ flux} \quad \text{for plumes}$$

β: thermal coefficient of expansion of the cloud fluid (1/K)

g: acceleration due to gravity (m/s^2)

ρ and C_p: density (kg/m^3) and specific heat (J/kg k) at constant pressure of the ambient fluid

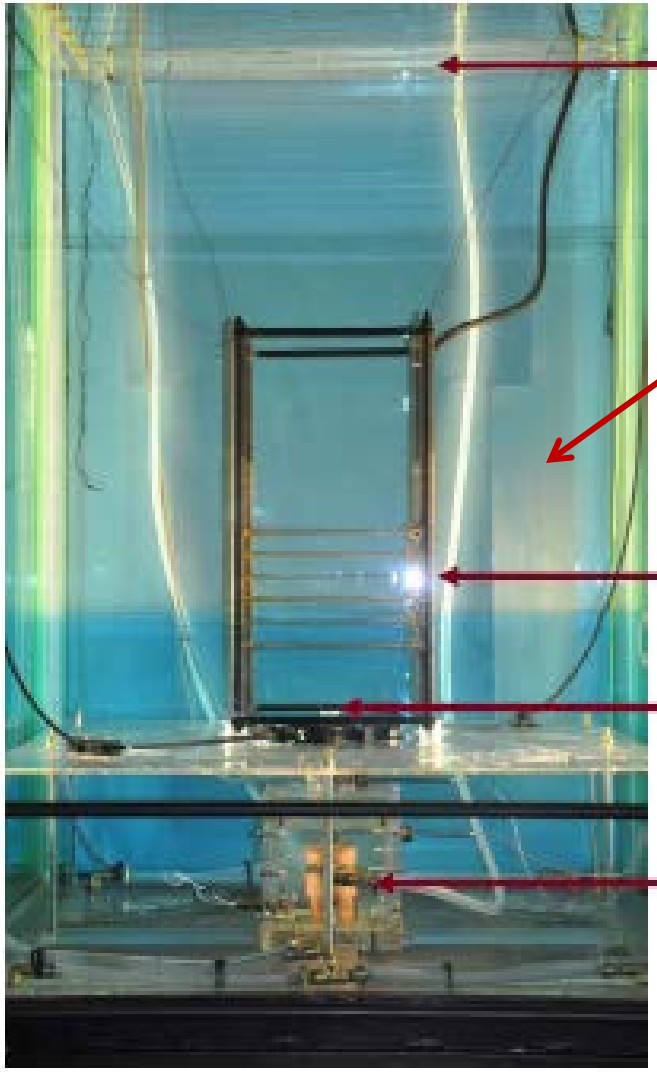
Q: total off-source heating rate (W)

b and U: length and velocity scales (*m* and *m/s*)

G can, in principle, vary in space and time

Bhat+narasimha,1996,JFM

EXPERIMENTAL SET-UP AT JNCASR



Surface heater

Constant-head reservoir

Deionized water

Test tank

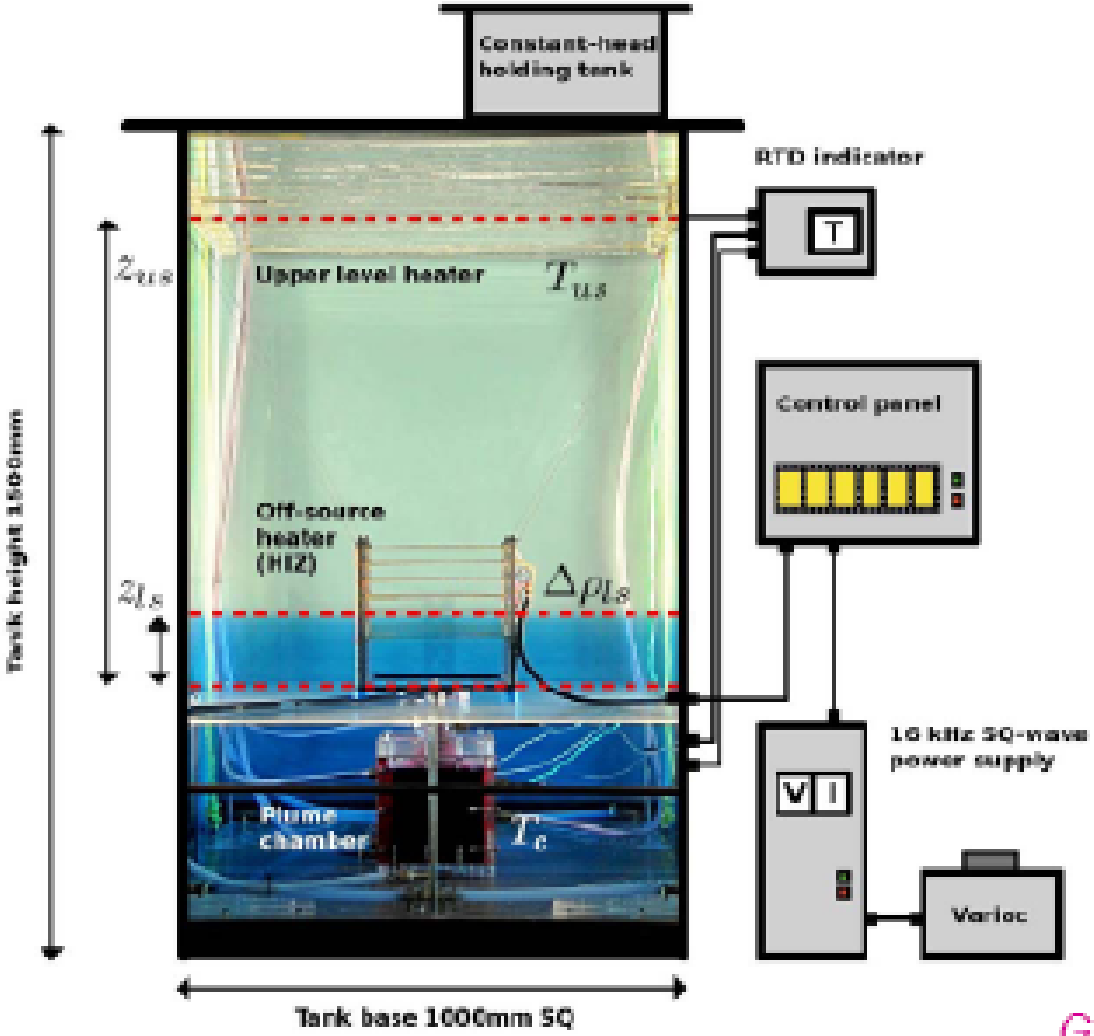
Heating grids

Inlet nozzle

Heating chamber for active fluid (electrically conducting)

EXPERIMENTAL SETUP

Experimental Setup



$$\mathrm{Re} = \frac{Ud}{\nu}$$

U : nozzle-exit velocity

d : nozzle diameter

T : Averaged temperature

z : Height measured from plane of nozzle exit

$\Delta\rho$: Density difference;

Subscripts:

ls, lower density stratification interface (dash-dot lines);

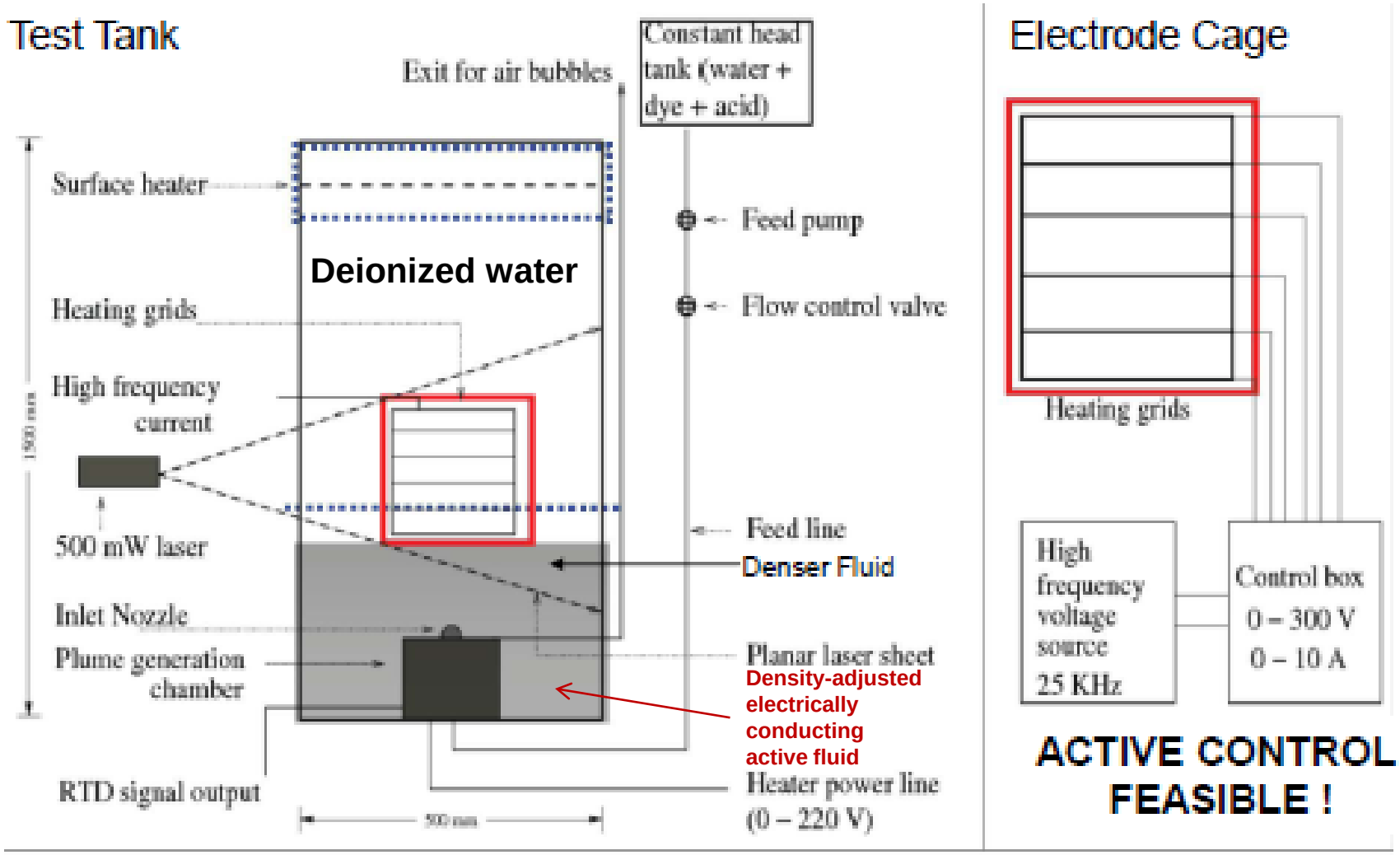
us, plane of free-surface heater;

c, chamber exit.

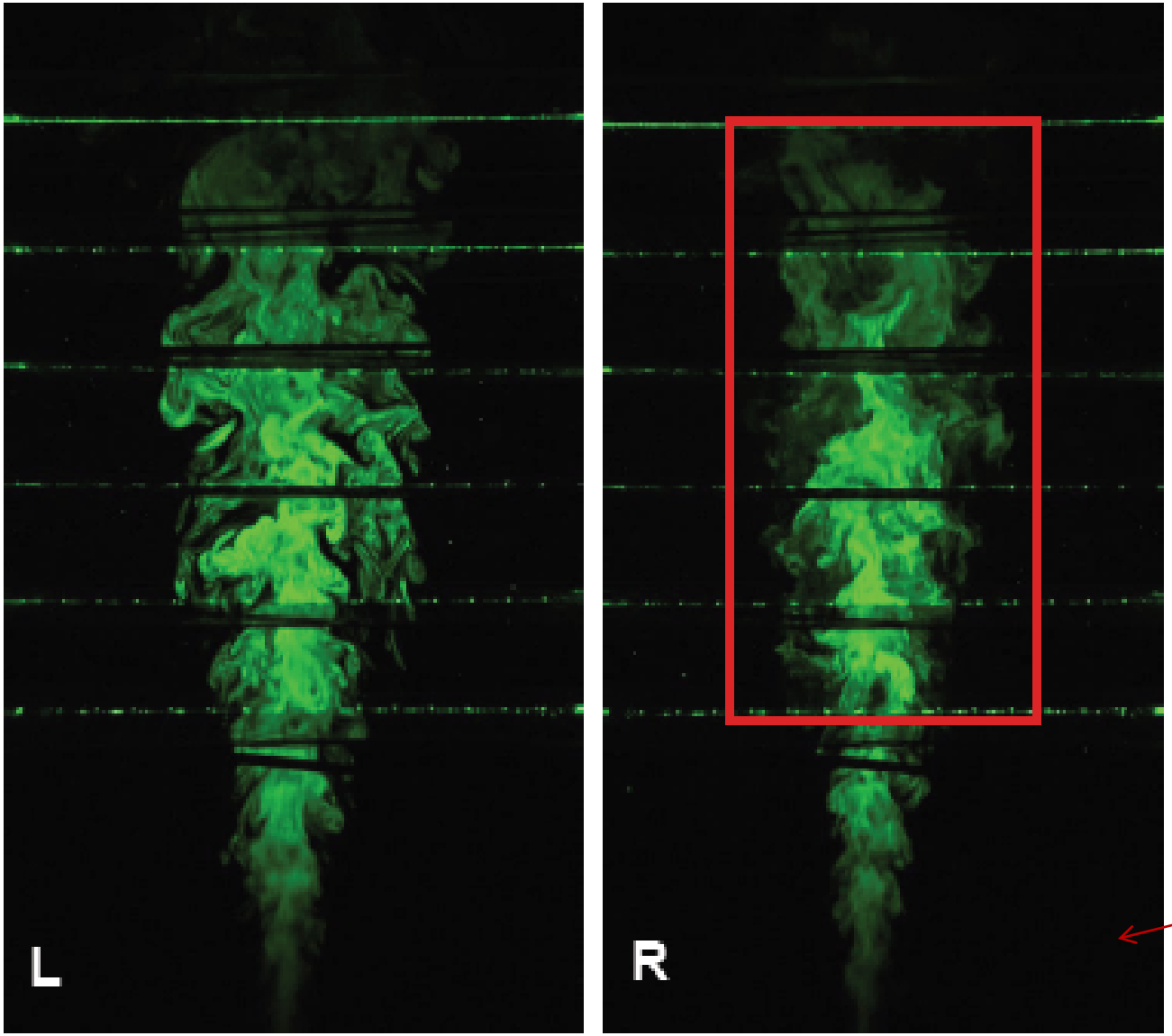
RTD: Resistance Temperature Detector

G(t) and G(z) possible to obtain

SCHEMATIC OF THE SIMULATOR



AXIAL SECTIONS OF PLUME WITH AND WITHOUT DIABATIC HEATING



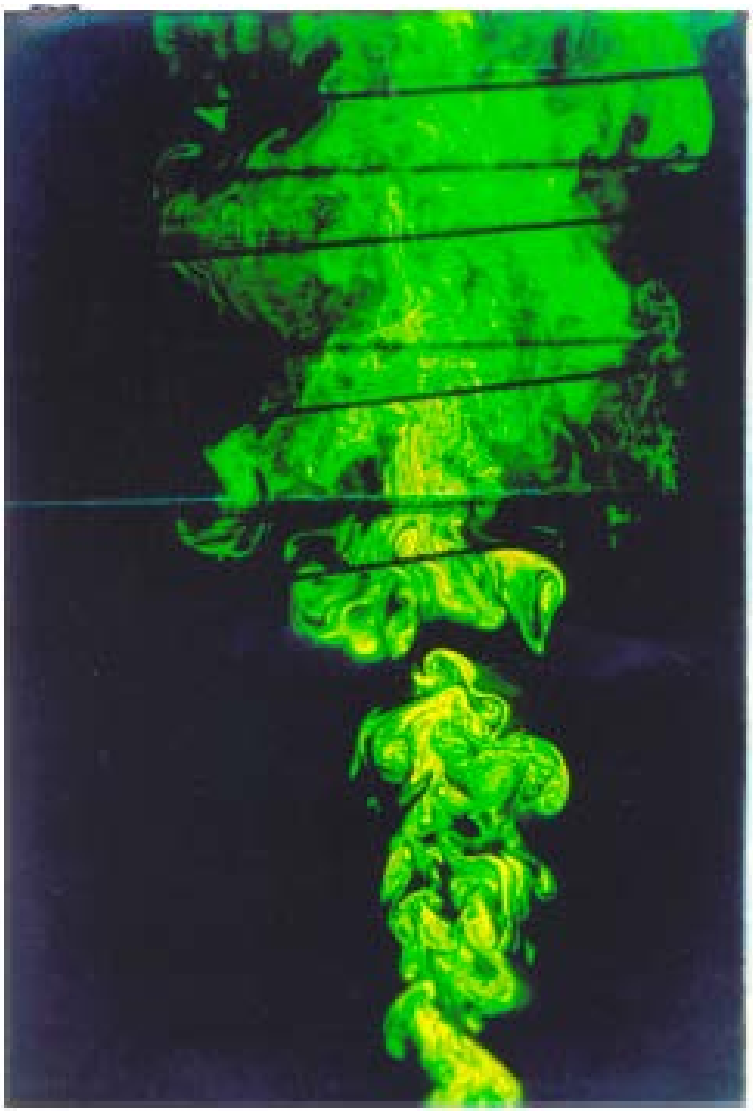
- *Re* = 2250
- Exit velocity at nozzle = 0.28 m/s
- $\Delta T = 30^{o}$ C (heating chamber)

L) $Q = 0$, $G = 0$

R) $Q = 1350$ *W*
$G = 13.8$

Heat injection zone

HEATING ALTERS FLOW STRUCTURE



heat injection

Venkatakrishnan et al. 1998 *Curr. Sci.*,
1999 *JGR*

COMPARISON WITH REAL CLOUDS

Classification as in the International Cloud Atlas (WMO)

Based mainly on appearance

Three genera and three species simulated

Genera: Cumulus
Alto- / Strato- cumulus

Species: Cu. Congestus
Cu. Mediocris
Cu. Fractus

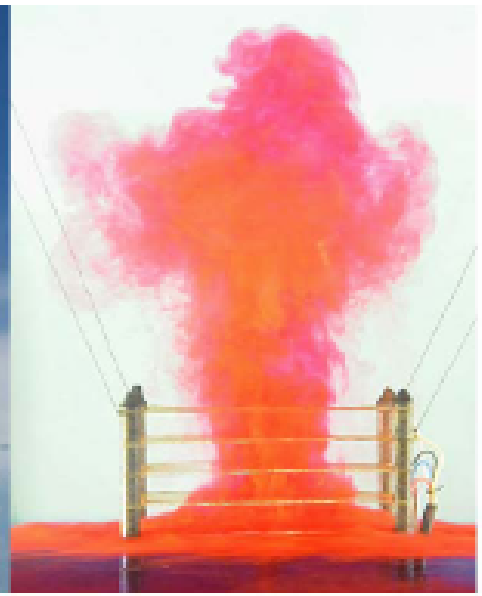
COMPARISON WITH REAL CLOUDS
Towers and Flowers

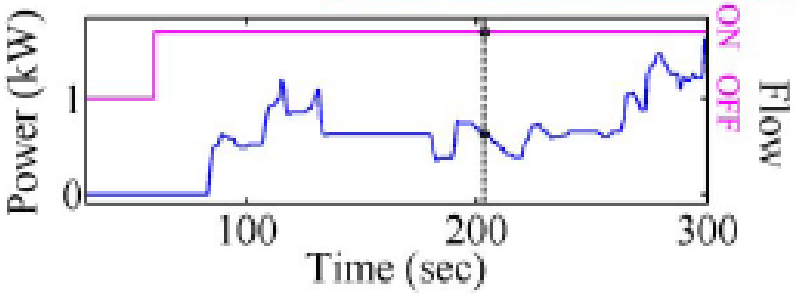
Comparison

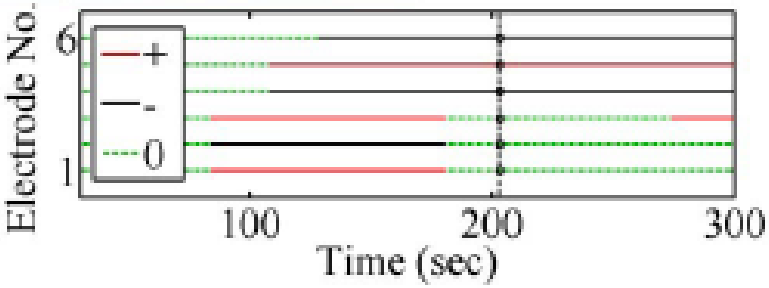
Cumulus Congestus

Tall, narrow,

tower-like







$Re \approx 3000$	$T_c = 30.8^oC$	$T_{us} = 33.9^oC$	$\Delta\rho_{ls} \approx 1kg/m^3$	$z_{ls} = 126.5mm$	$z_{us} = 869mm$

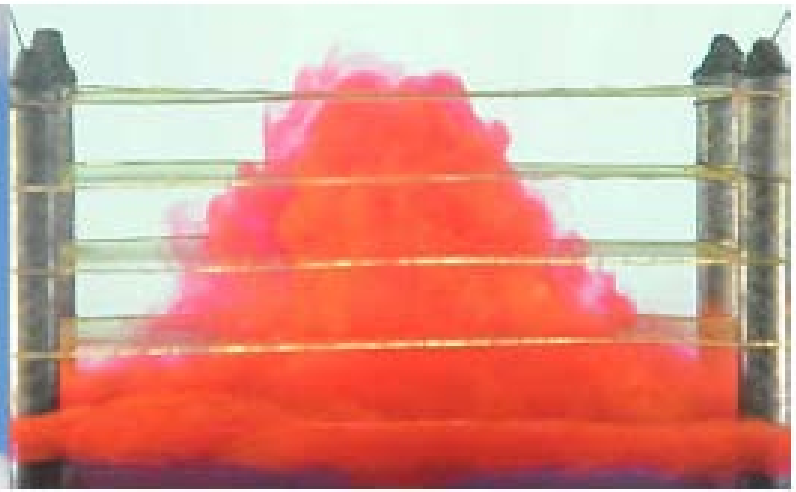
Real Cloud Photo Credit: http://img.photobucket.com/albums/v493/scubastza/Blog%20Stuff/cloud.jpg

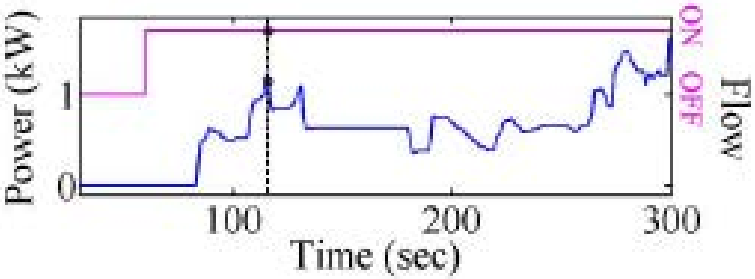
COMPARISON WITH REAL CLOUDS

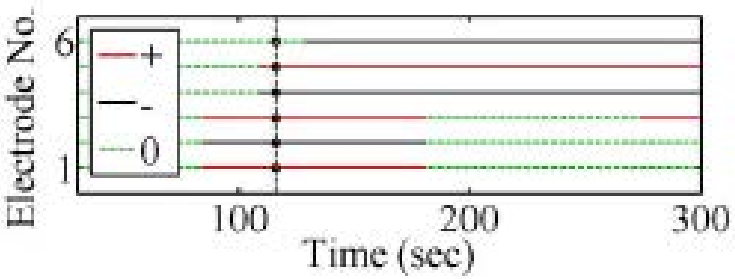
Comparison

Cumulus Congestus

Striking Resemblance







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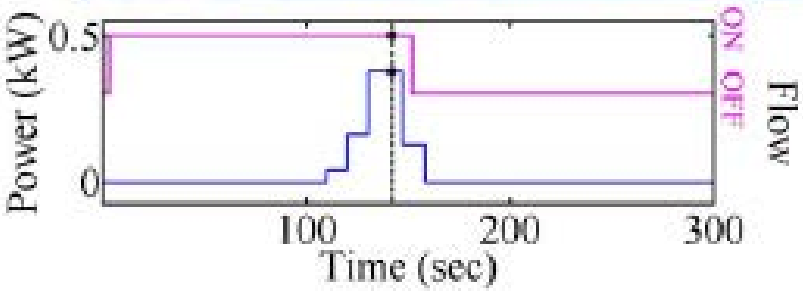
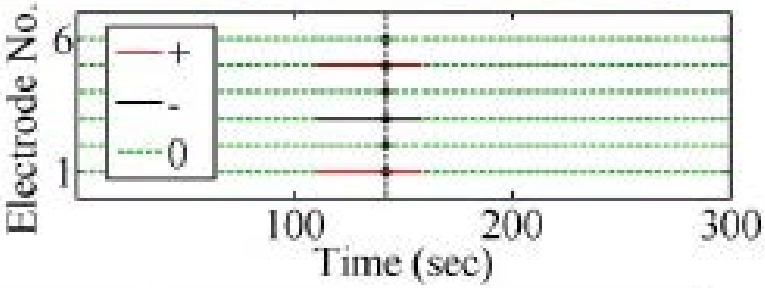
Fluffy, sharp edges, flower-like

COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus





$Re = 560$	$T_c = 25^oC$	$T_{us} = 28^oC$	$\Delta\rho_{ls} \approx 1kg/m^3$	$z_{ls} = 145mm$	$z_{us} = 980mm$

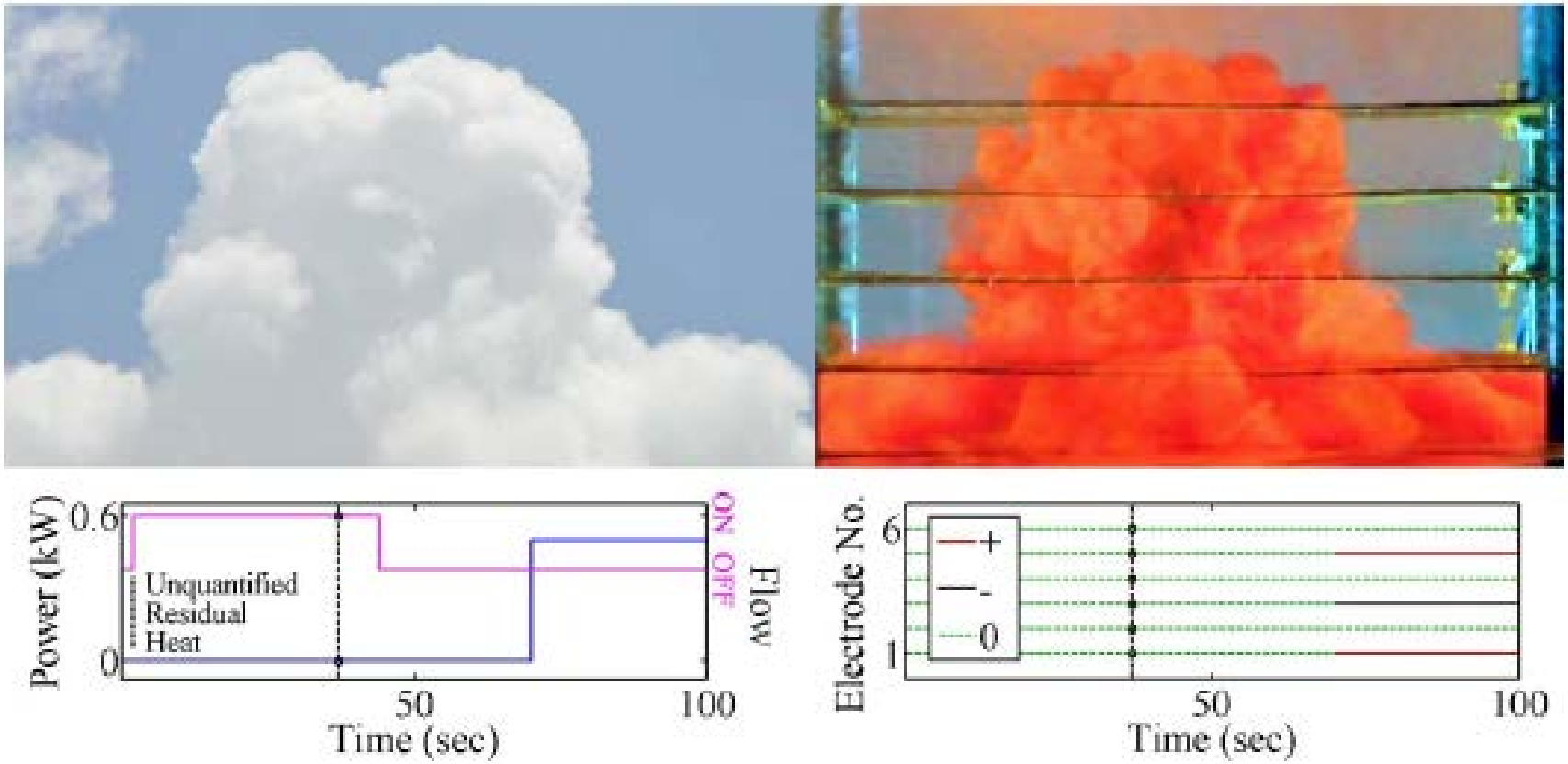
Real Cloud Photo Credit: Aditya Konduri (near Italy; 9-10 km height)

COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus

Different Shapes



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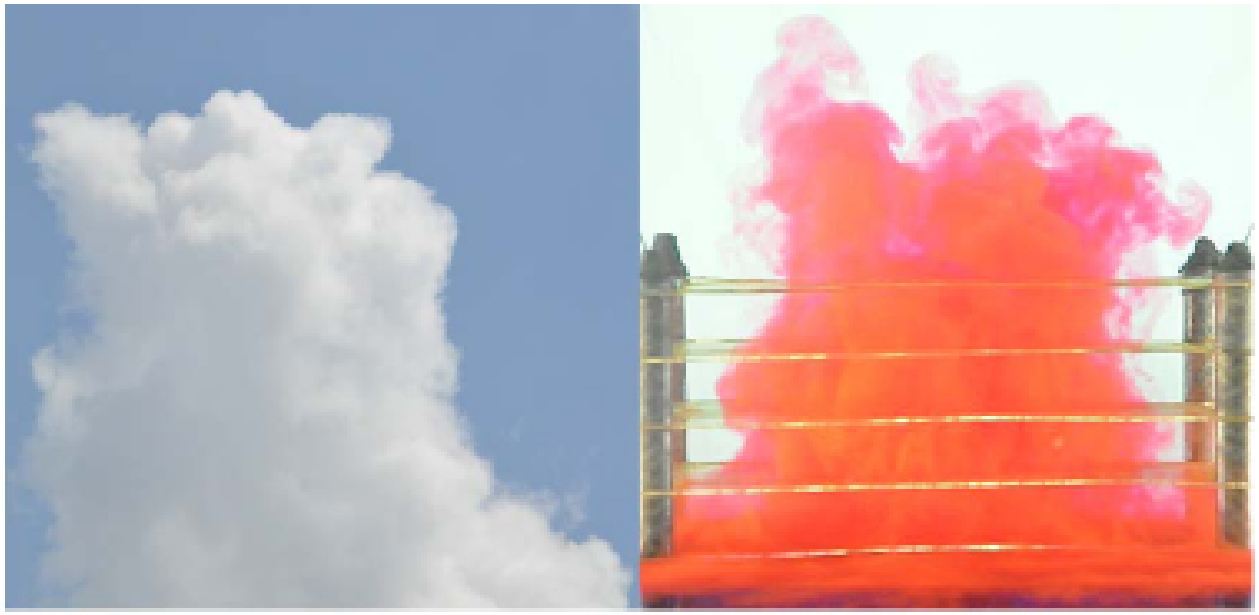
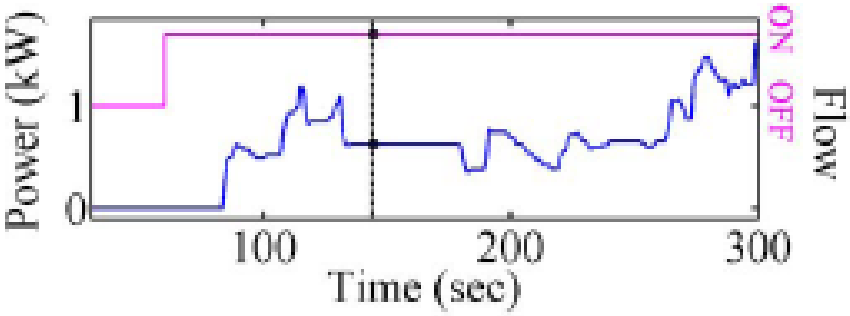
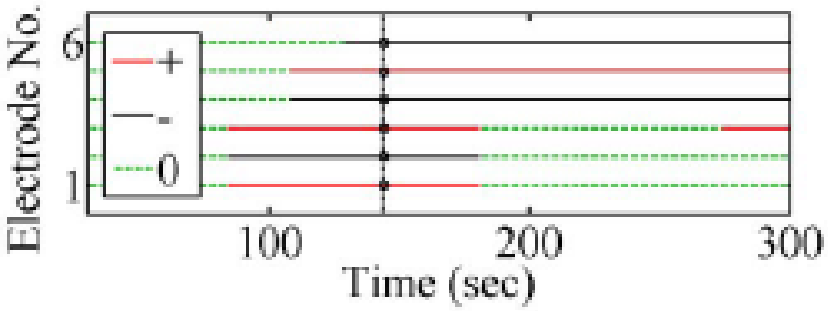
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus





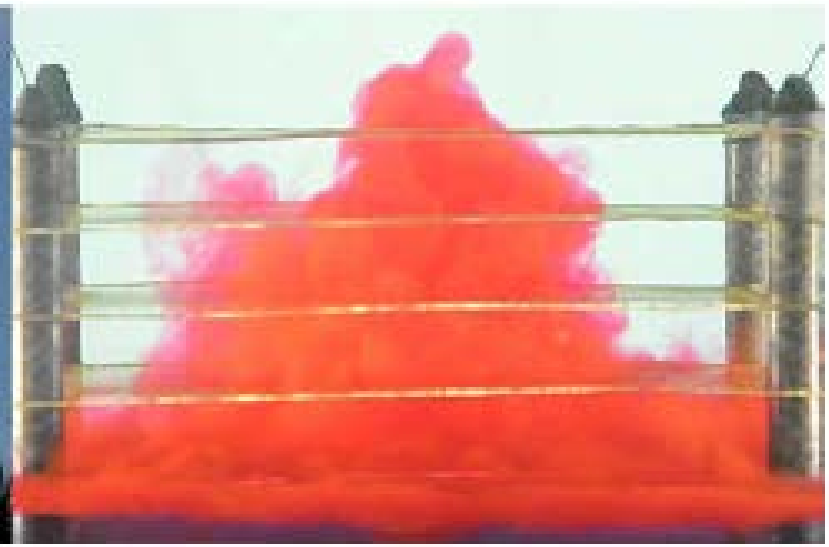


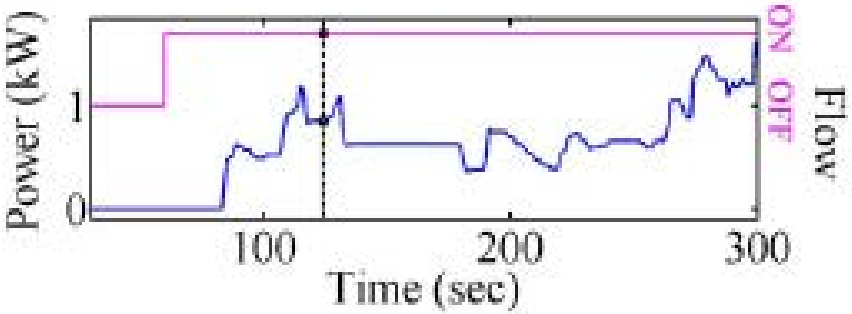
$Re \approx 3000$	$T_c = 30.8^o\mathrm{C}$	$T_{us} = 33.9^o\mathrm{C}$	$\Delta\rho_{ts} \approx 1\mathrm{kg/m^3}$	$z_{ts} = 126.5\mathrm{mm}$	$z_{us} = 869\mathrm{mm}$

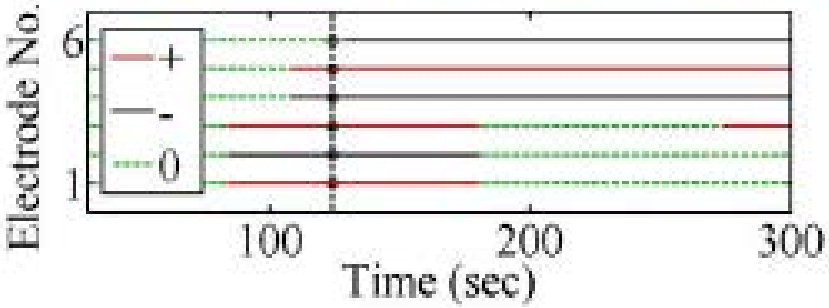
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus







$Re \approx 3000$	$T_c = 30.8°\mathrm{C}$	$T_{us} = 33.9°\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 126.5\mathrm{mm}$	$z_{us} = 869\mathrm{mm}$

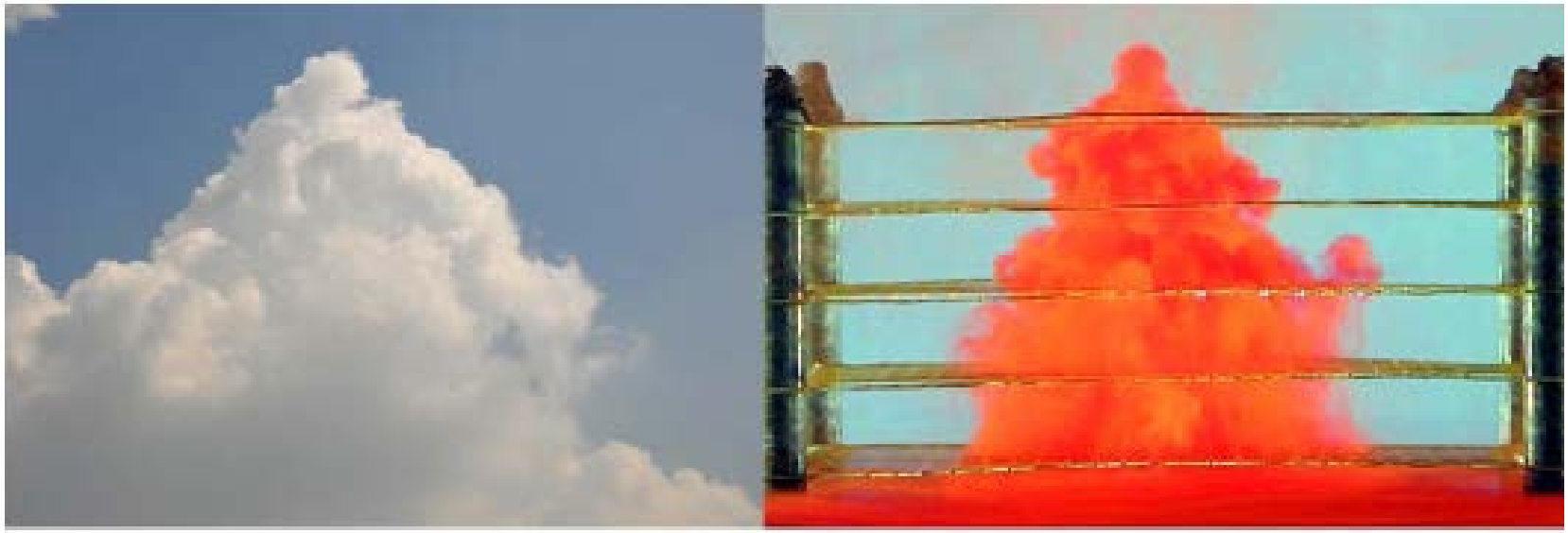
COMPARISON WITH REAL CLOUDS

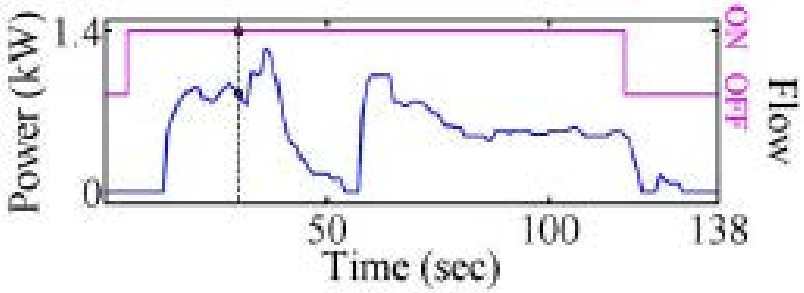
Comparison

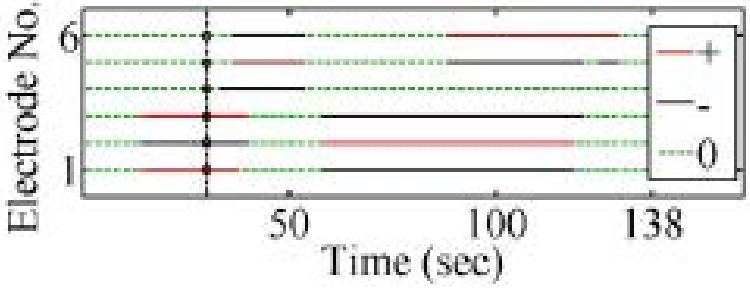
Cumulus Congestus

Effect of heating history and distribution

Three instants





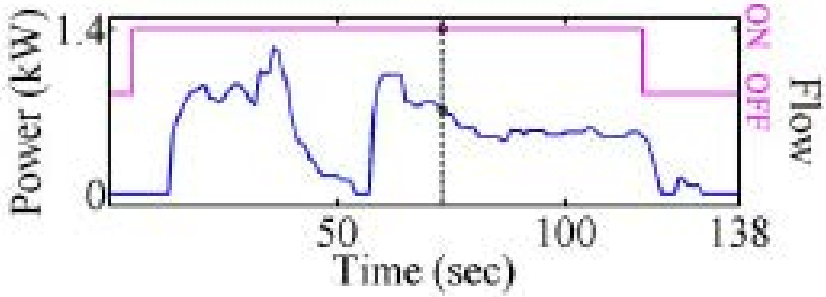


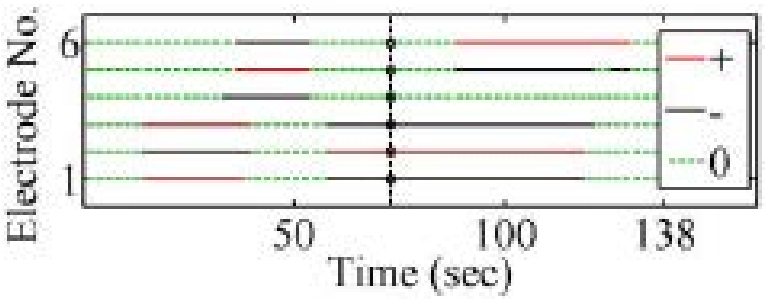
$Re \approx 650$	$T_c = 35.5^oC$	$T_{us} = 35^oC$	$\Delta\rho_{ls} \approx 1kg/m^3$	$z_{ls} = 126.5mm$	$z_{us} = 869mm$

COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus





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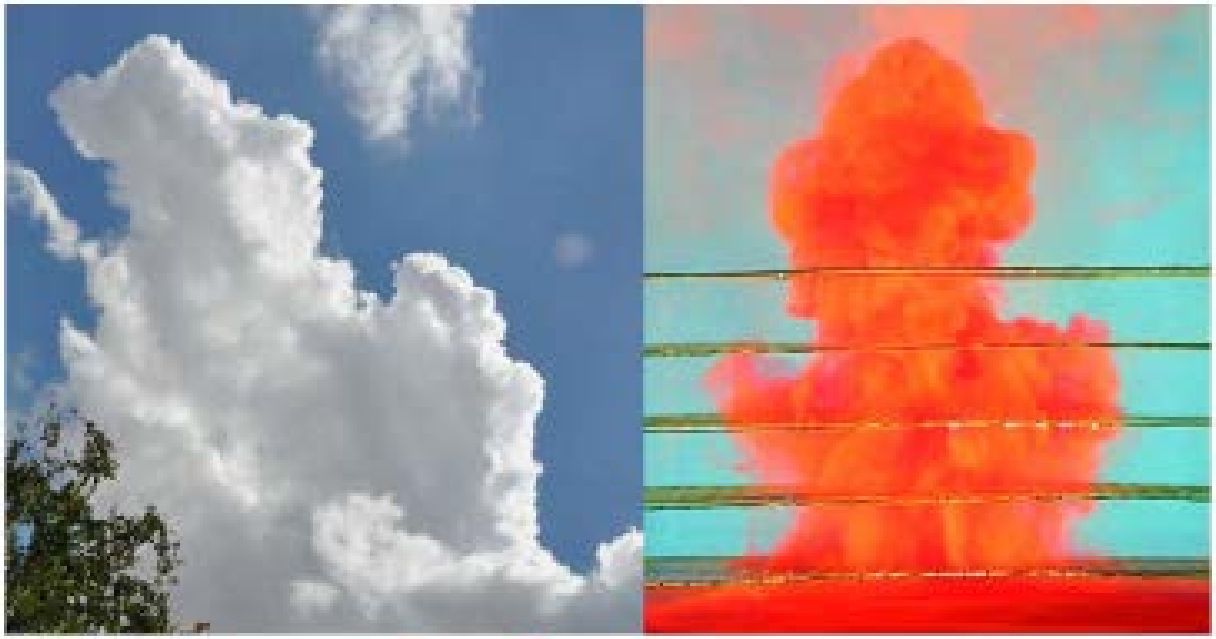
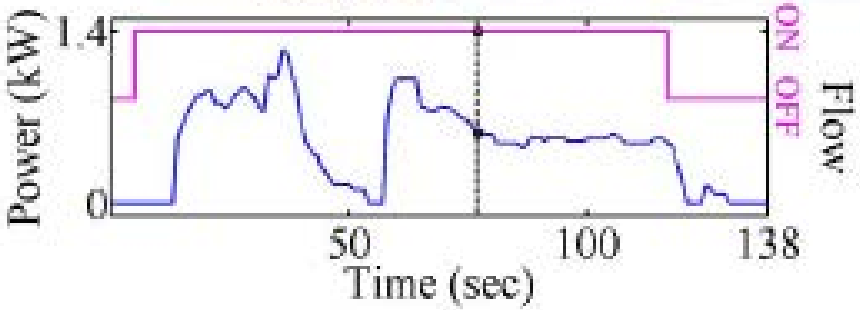
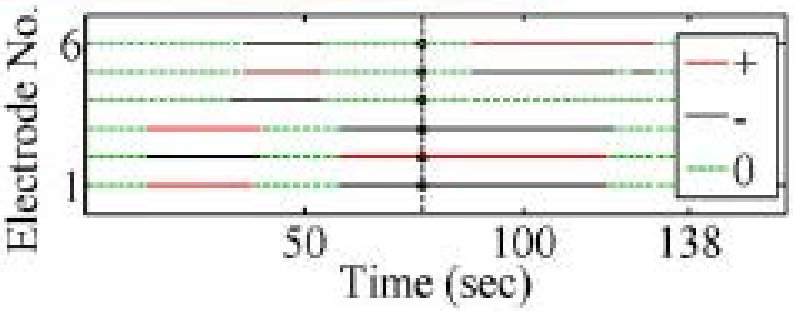
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus







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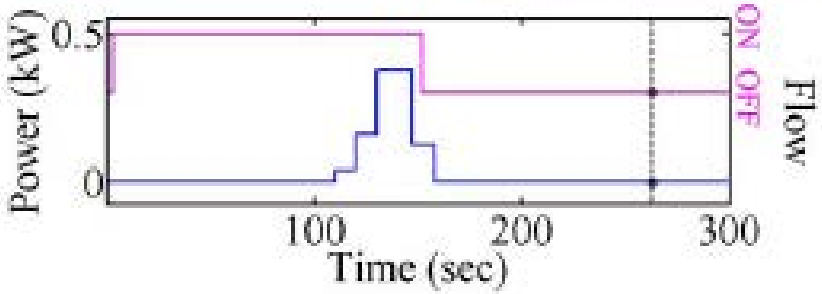
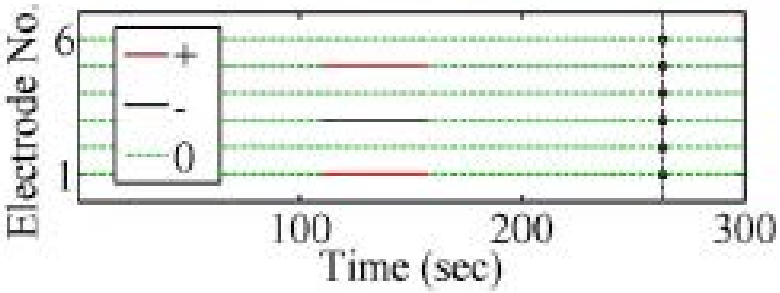
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Mediocris





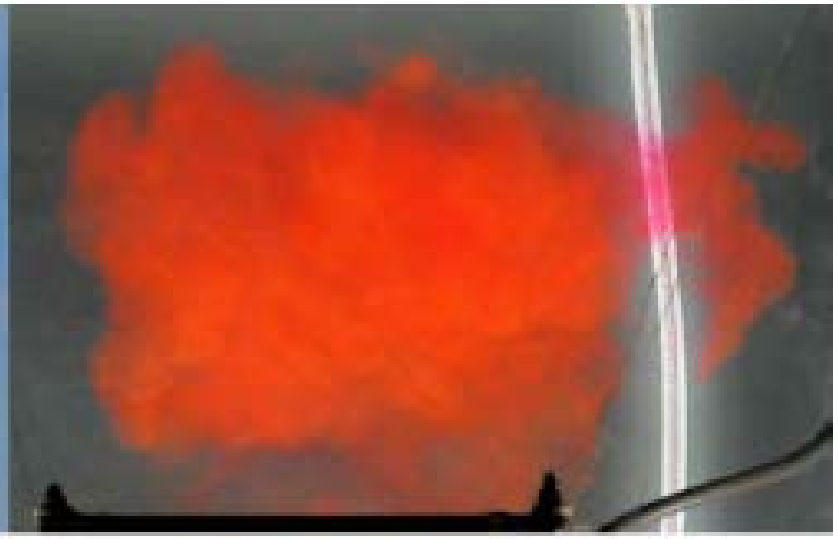
$Re = 560$	$T_c = 25^o\mathrm{C}$	$T_{us} = 28^o\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 145\mathrm{mm}$	$z_{us} = 980\mathrm{mm}$

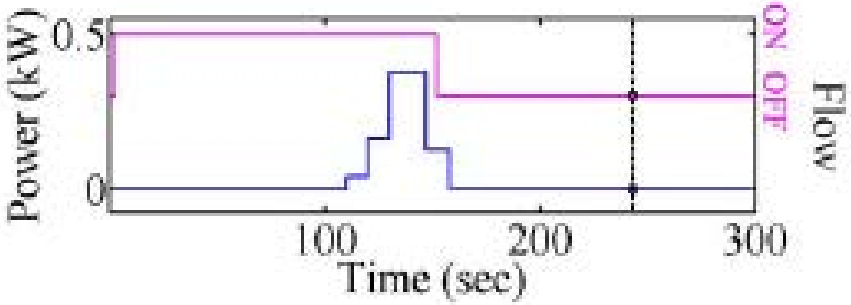
Hovering (slowly sinking), Evaporating

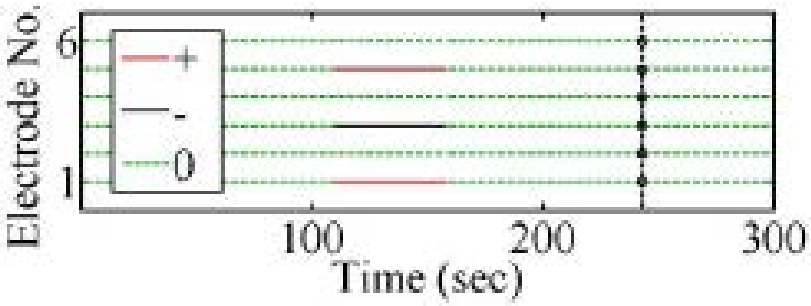
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Mediocris







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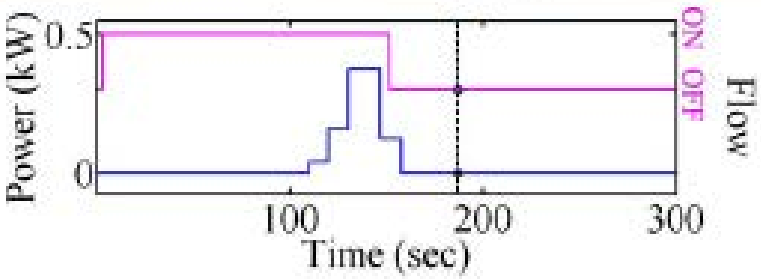
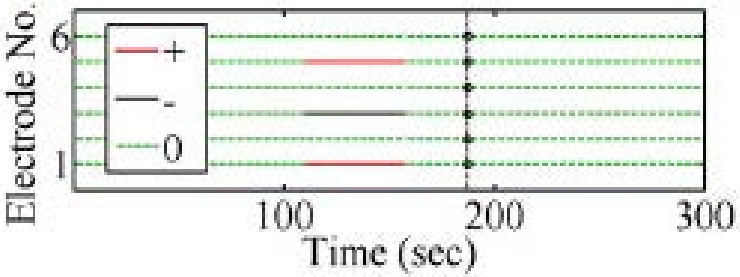
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Fractus





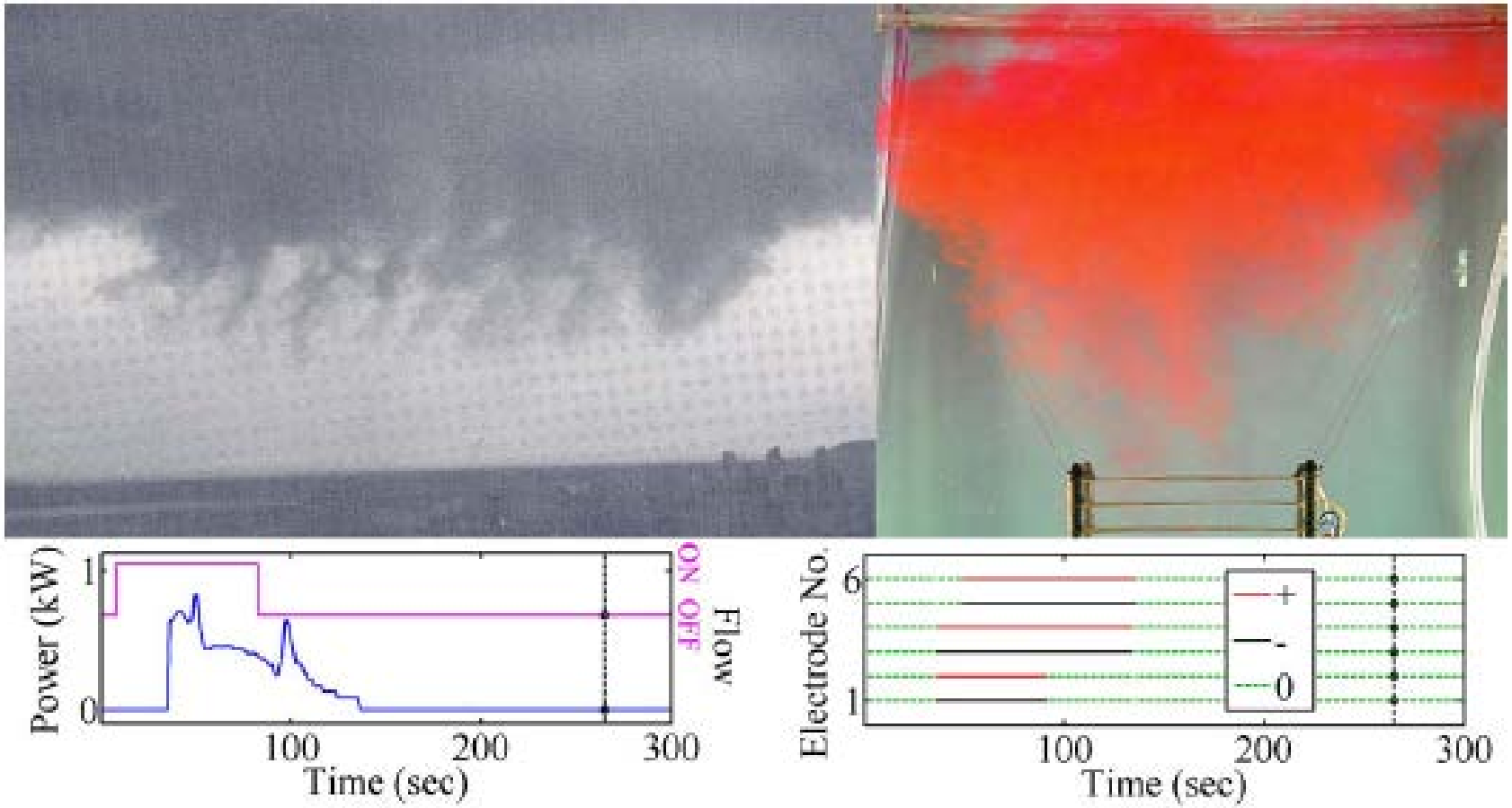
$Re = 560$	$T_c = 25^o\mathrm{C}$	$T_{us} = 28^o\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 145\mathrm{mm}$	$z_{us} = 980\mathrm{mm}$

Jagged edges, dissolving stage

COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Fractus



$Re \approx 1150$	$T_c = 35.8^o\mathrm{C}$	$T_{us} = 35.7^o\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 126.5\mathrm{mm}$	$z_{us} = 869\mathrm{mm}$

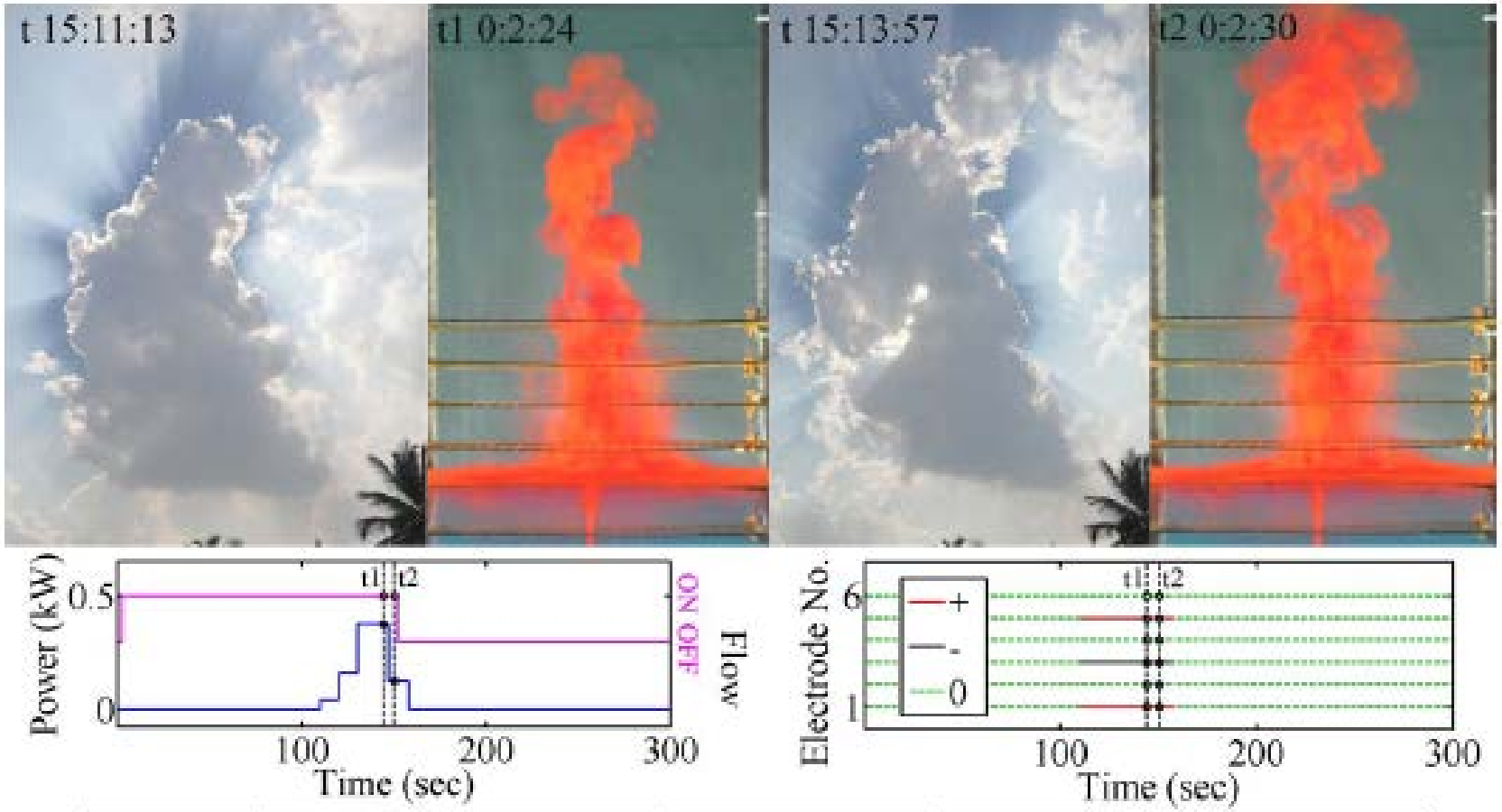
Scud, seen during monsoons

Real Cloud Photo Credit: Scorer Plate 43

COMPARISON WITH REAL CLOUDS

Comparison

Cloud-top break away



$Re = 560$	$T_c = 25^oC$	$T_{us} = 28^oC$	$\Delta\rho_{ls} \approx 1kg/m^3$	$z_{ls} = 145mm$	$z_{us} = 980mm$

Simulating cloud processes

COMPARISON WITH REAL CLOUDS

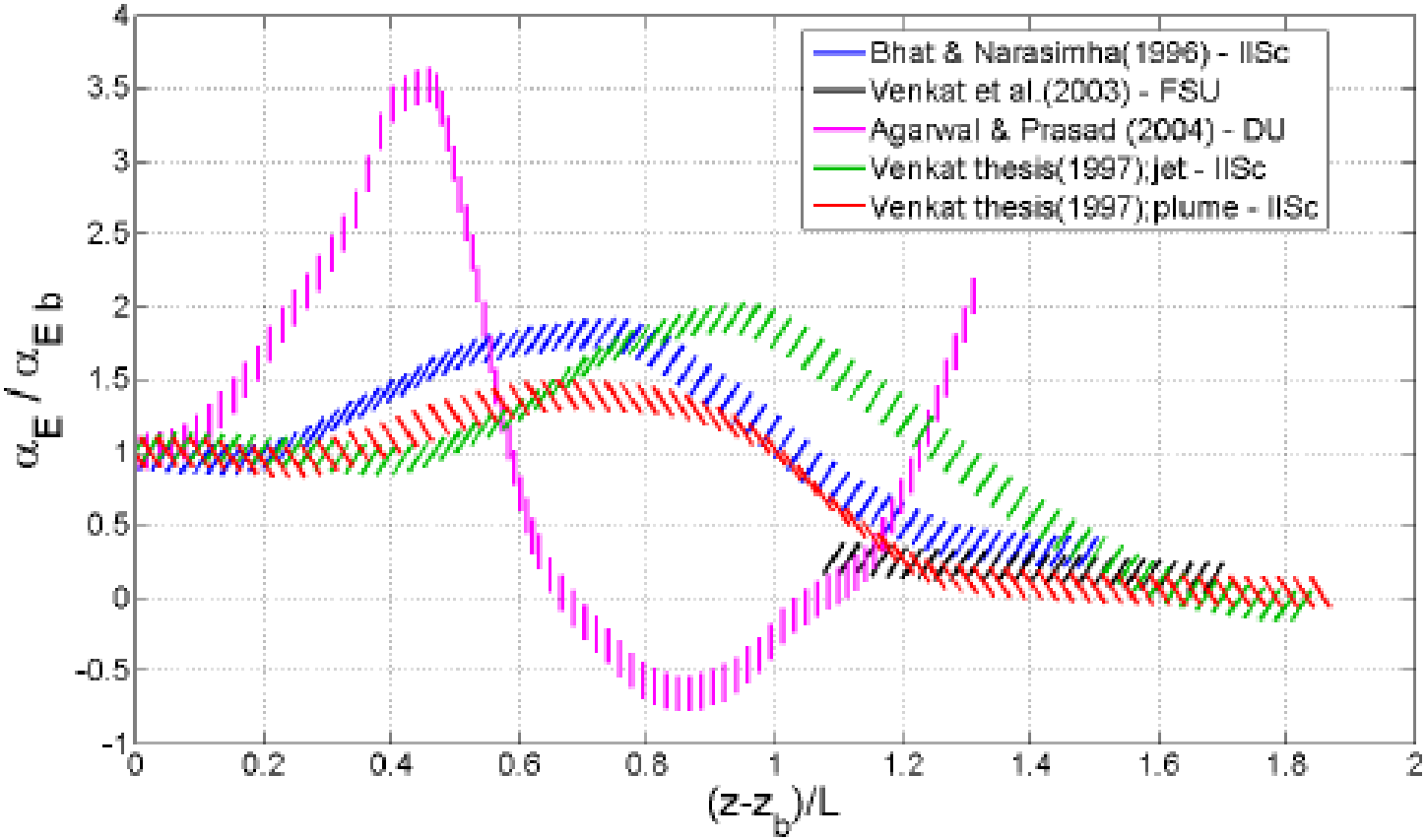
- The important parameters identified

  1. Flow history
  2. Heating profile history
  3. Lower and upper stratification (heights and magnitudes)
  4. Source momentum / buoyancy flux

- **Different combinations can give wide variety of cumulus shapes, types, flows**

COMPARISON WITH REAL CLOUDS

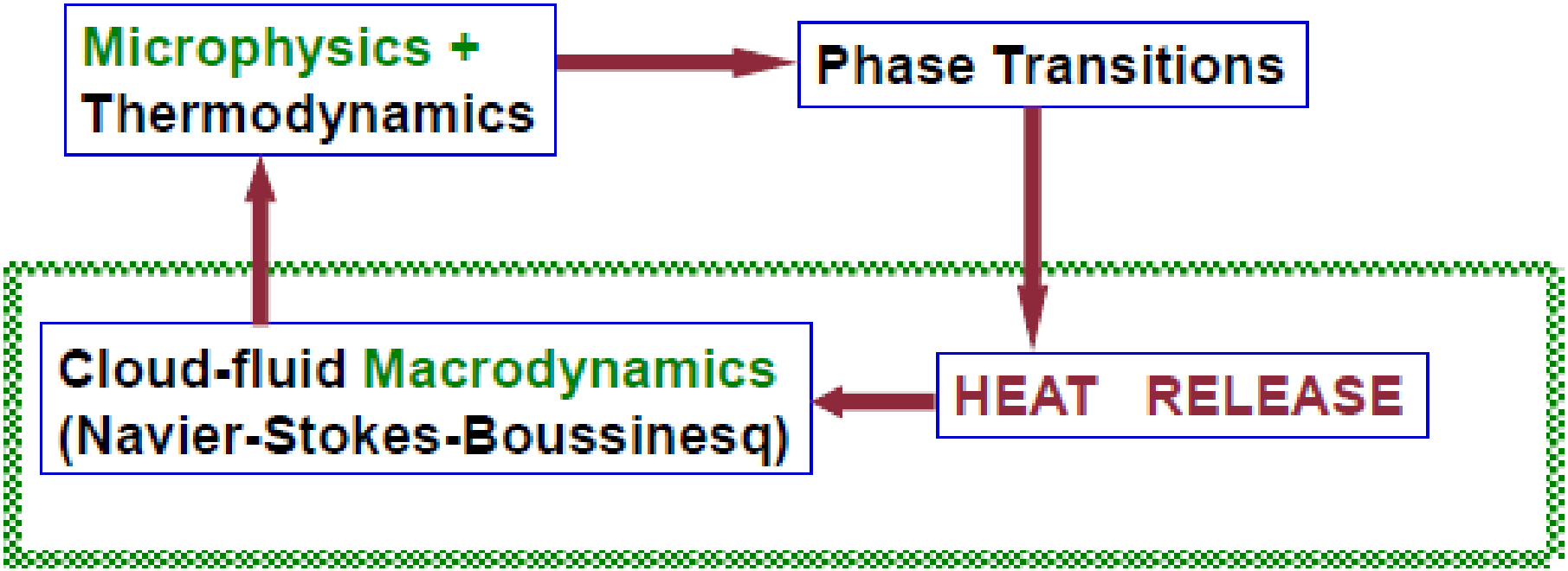
Entrainment Coefficient



$$\alpha_E = \frac{dm}{dz} \Big/ \left(2\pi b_u U_c\right)$$

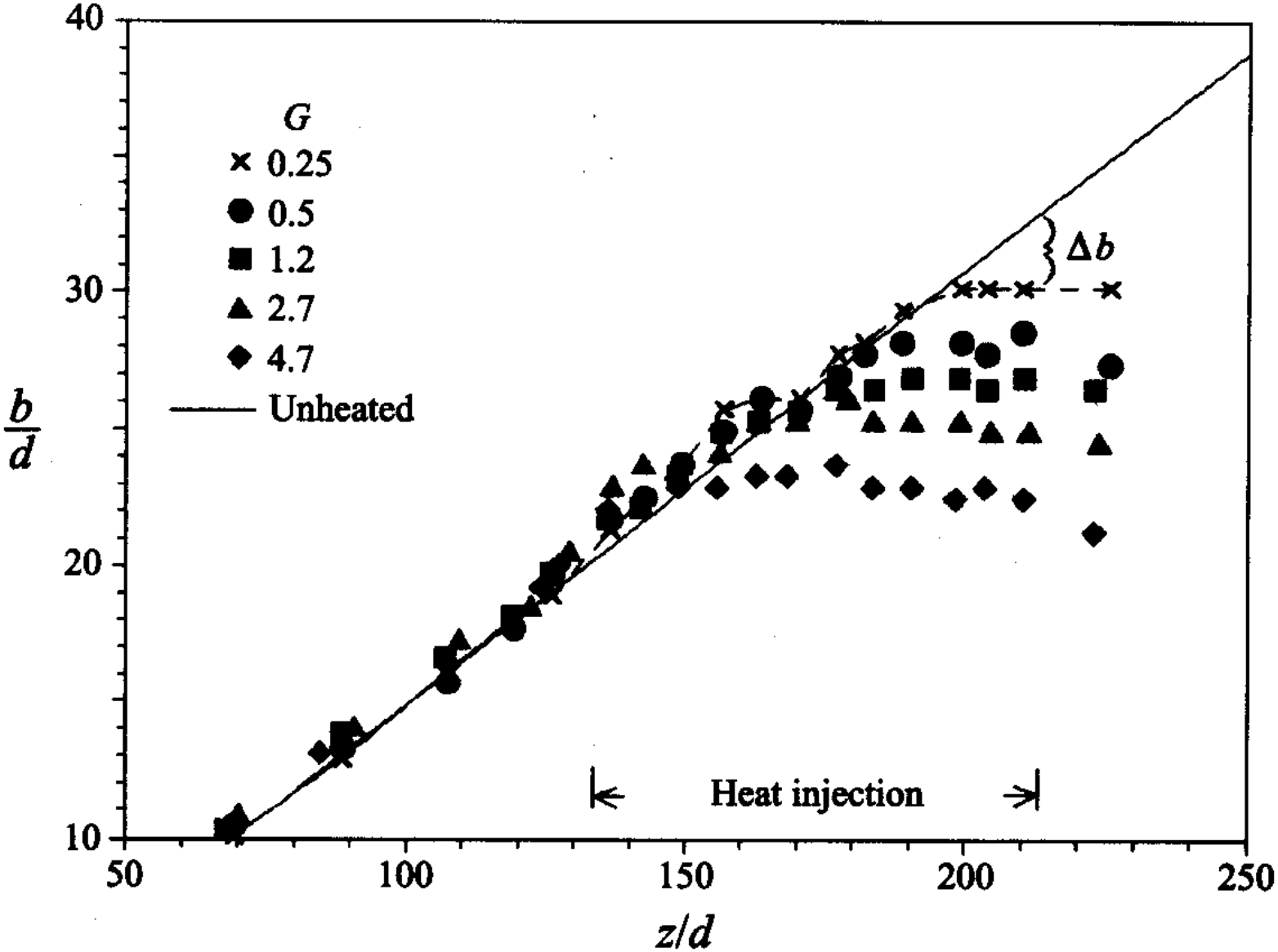
m : integrated mass flux, b_u : velocity width of the flow
Uc : mean centerline velocity
L : height of HIZ, Z_b : beginning of HIZ

FIRST ORDER NON-PRECIPITATING CUMULUS SYSTEM



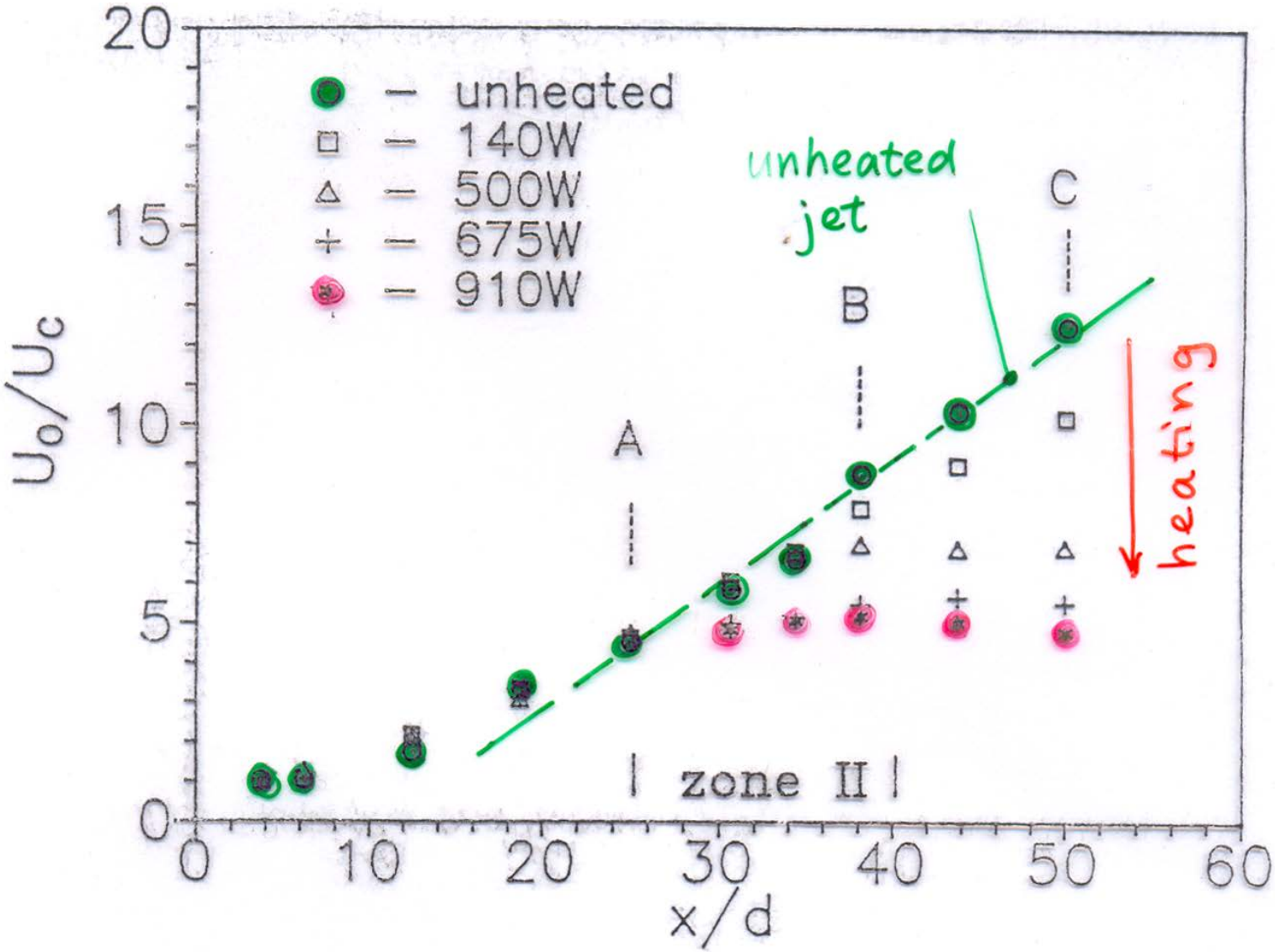
STEADY CLOUD FLOWS

JET WIDTH



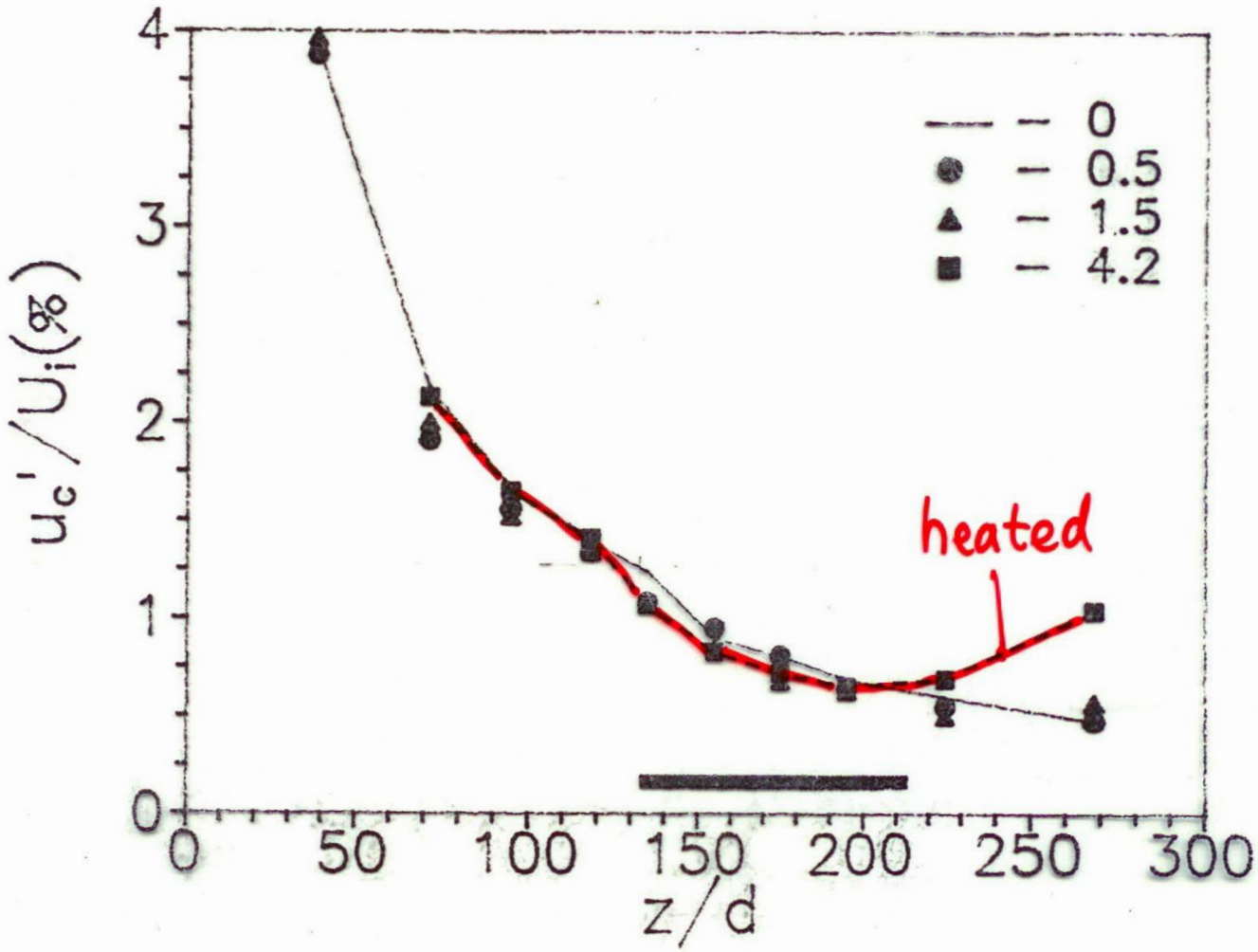
Stream-wise variation of scalar jet width at different values of the heating parameter Bhat, RN 1996, *JFM*

HEATING ACCELERATES FLOW

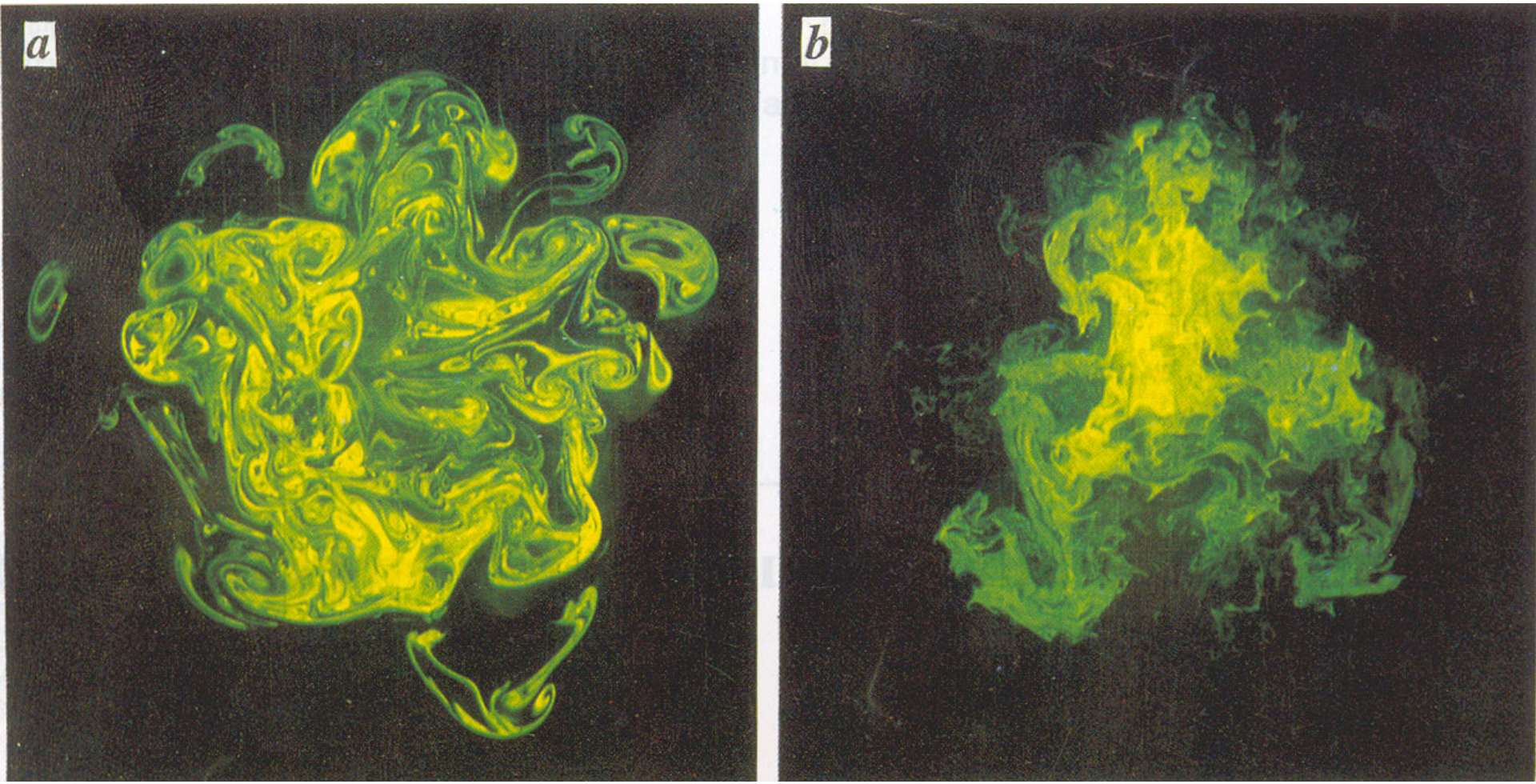


Variation of the axial component of the centreline velocity in the heated jet. Re_o =1480 and d = 8 mm Bhat, RN 1996, *JFM*

TURBULENCE IN CLOUD-FLOW



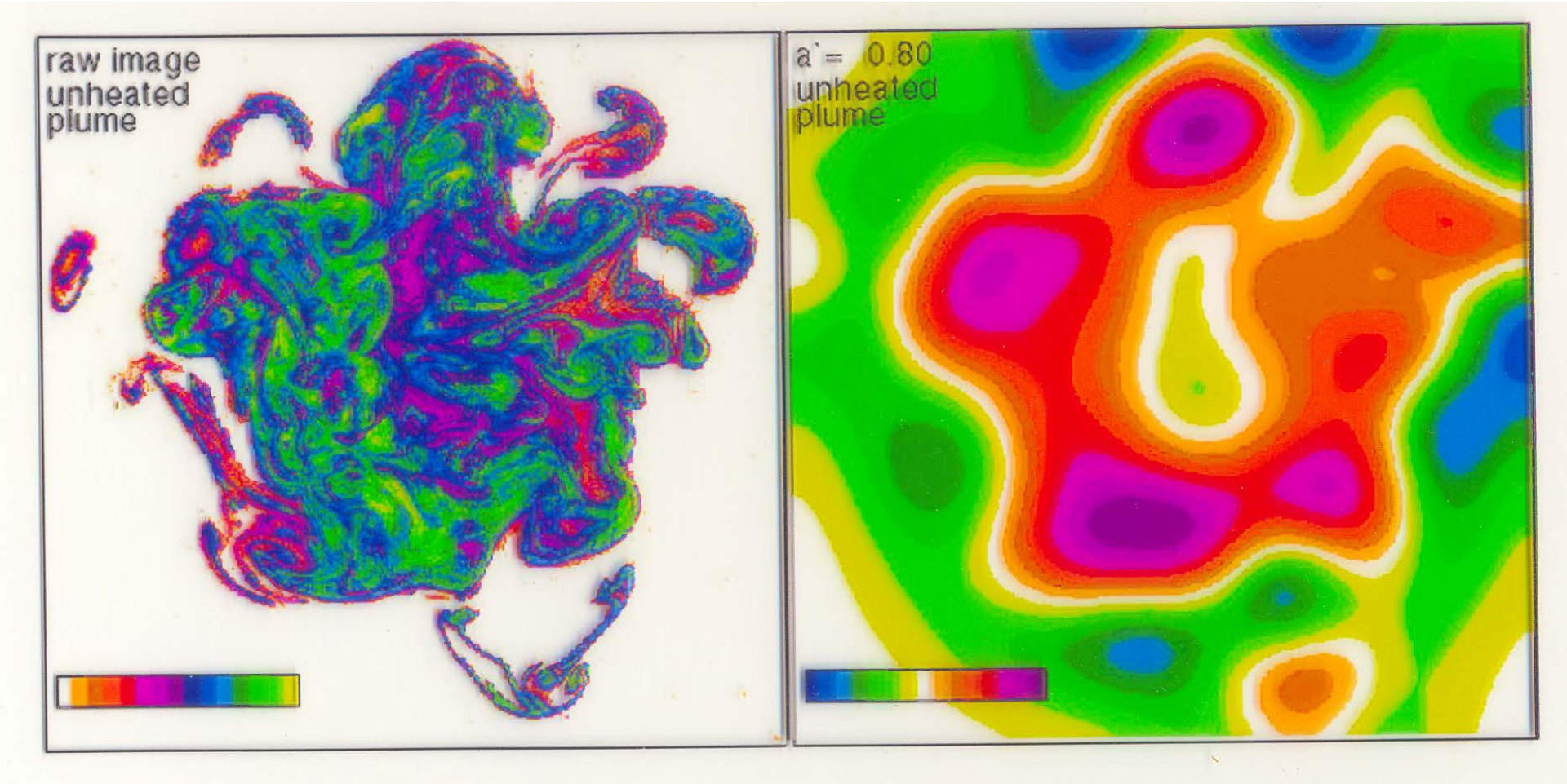
(ORDINARY) PLUME AS IT BECOMES CLOUD-PLUME



Diametral sections of ordinary and cloud plume at $z/d = 79.4$

Venkatakrishnan et al. 1998 *Curr. Sc.*

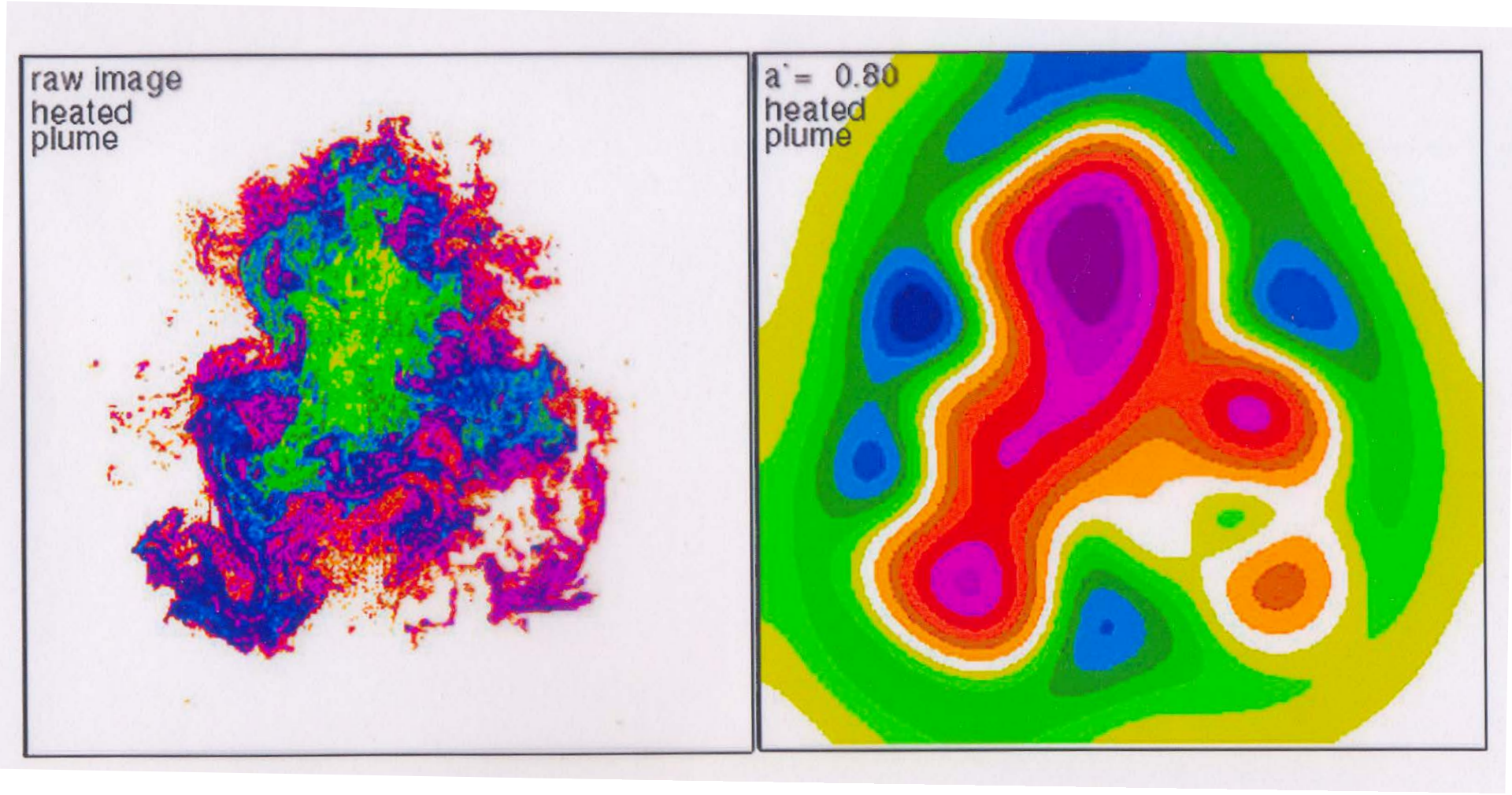
WAVELETS REVEAL HIDDEN ORDER, ORDINARY PLUME



Turbulent chaos conceals lobed vortex ring ?

Narasimha et al. 2002 *Expts. Fl.*, Srinivas+ *2007* JoT

CLOUD PLUME: UNMIXED CORE



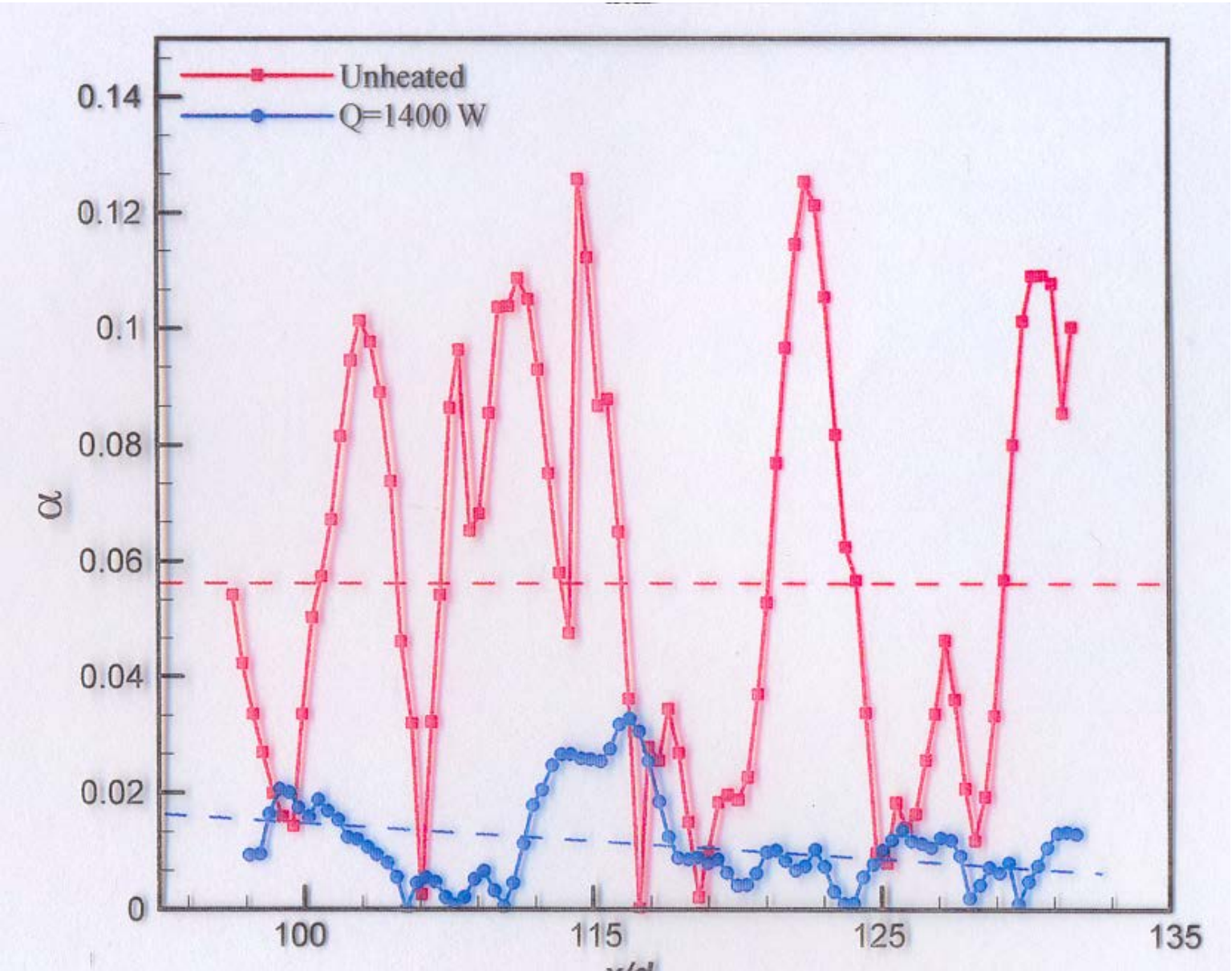
RN+ 2002 *Expts. Fl.*

Entrainment Coefficient (α_e)

- Taylor's definition: Derived from self-similar flows (Morton et al 1956)

$$\frac{dm}{dz} = 2\pi b_u \alpha_e U_c$$

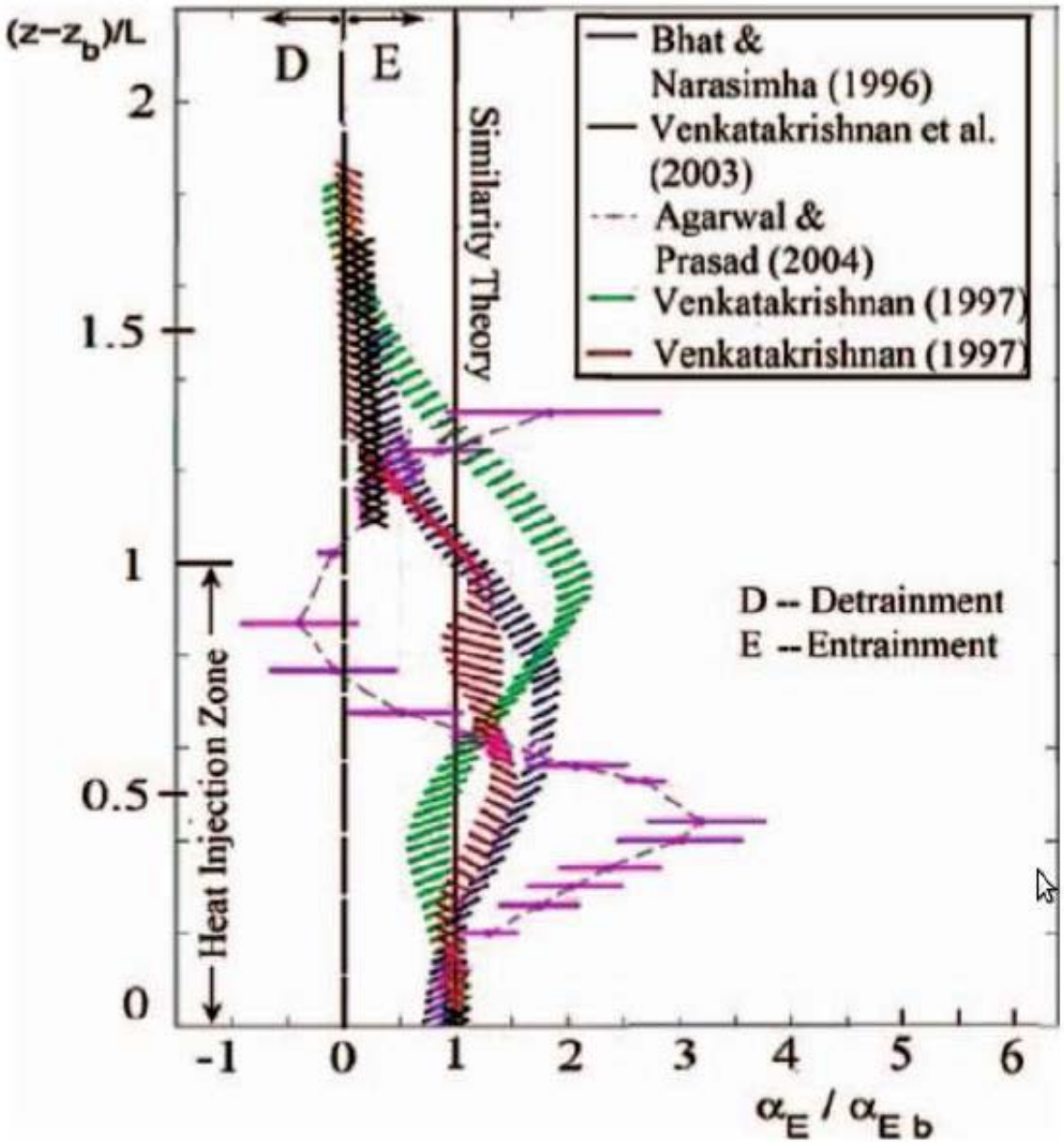
VARIATION OF ENTRAINMENT COEFFICIENT



Episodic variation of entrain-ment coefficient with axial distance

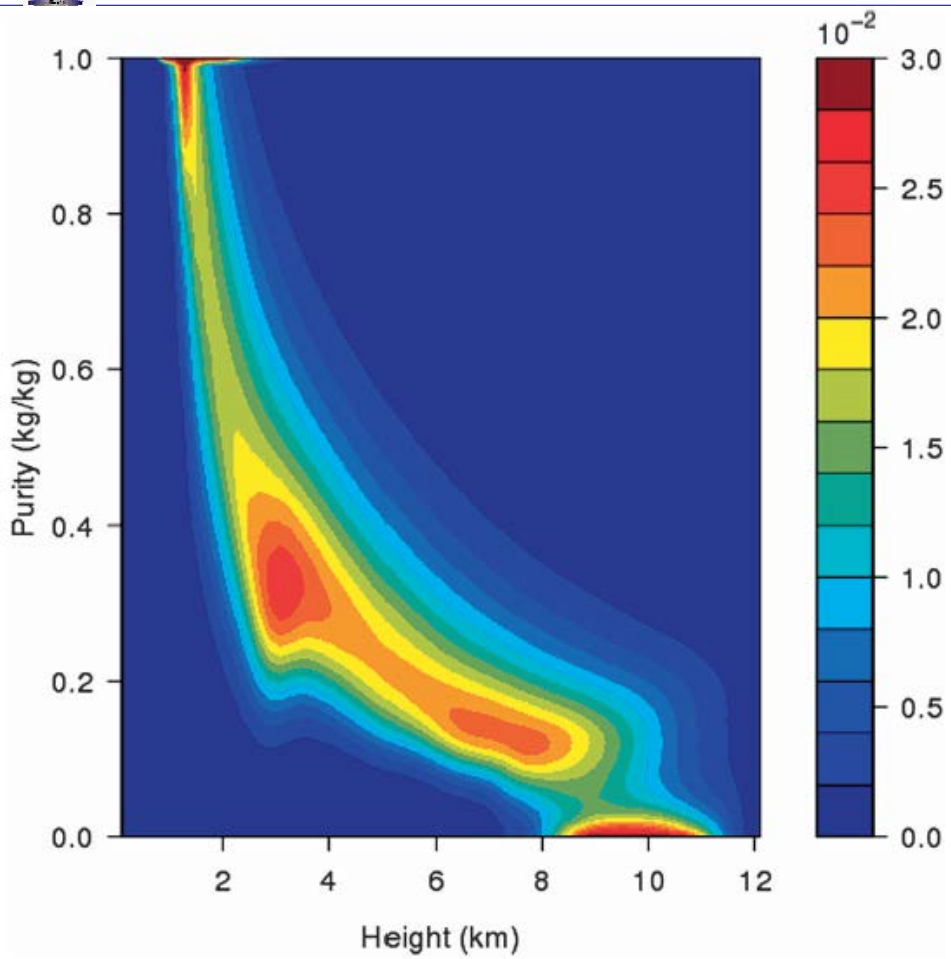
Venkata-krishnan + 2003 *Curr. Sci.*

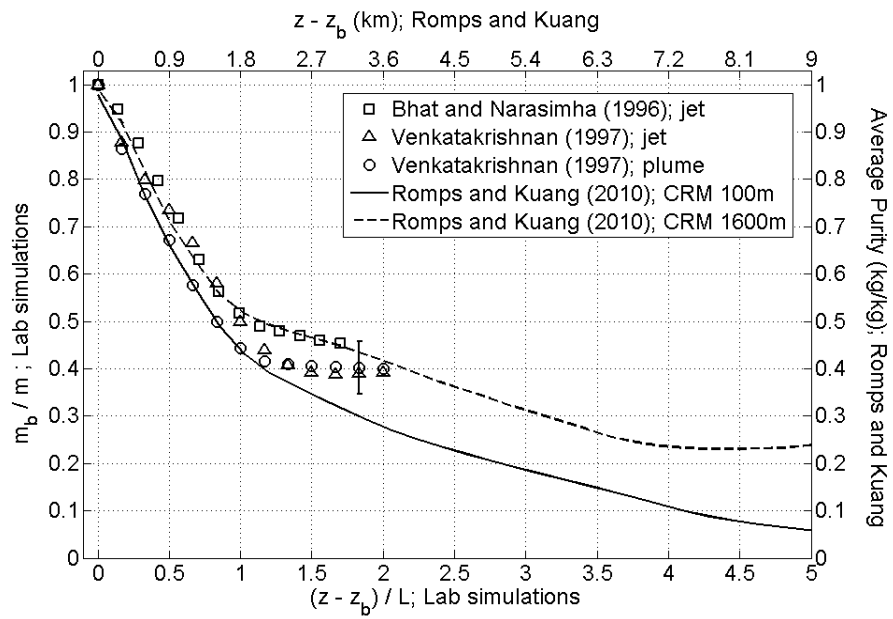
Previous Steady State Experiments



Diwan+ 2012

DILUTION AND PURITY





Romps & Kuang 2010 JAS

Comparison with Lab results (RN+2011PNAS)

A MODEST PROPOSAL

A Cumulus Cloud Flow
is a Special Example of a

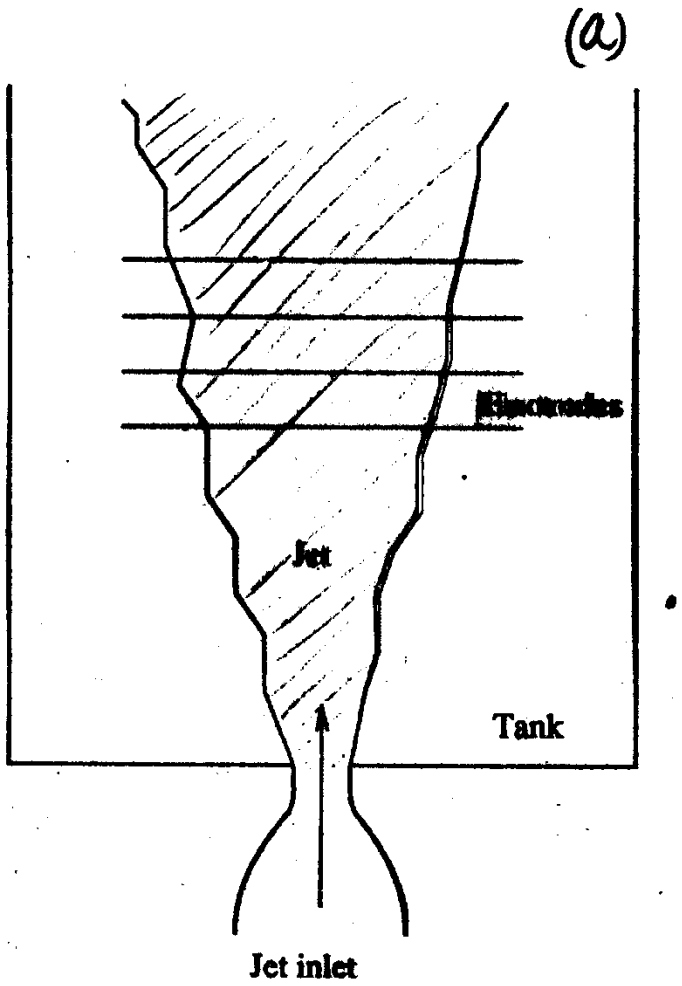
TRANSIENT DIABATIC PLUME

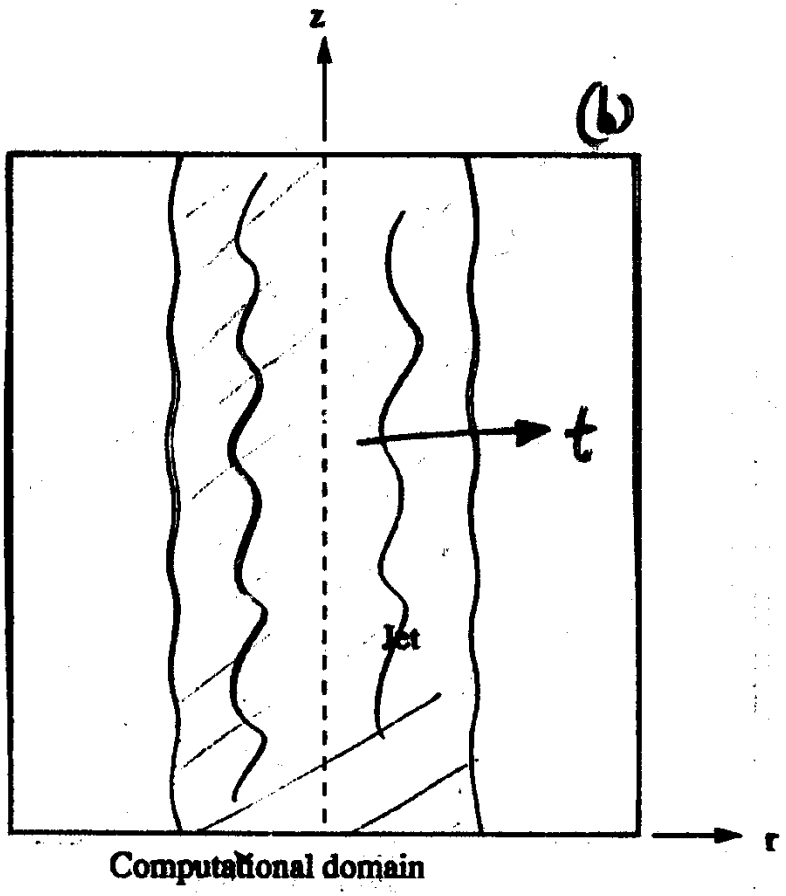
CYBER CLOUDS

SPECTRAL METHODS

Code: Megha 1

LABORATORY SETUP VERSUS TEMPORAL SIMULATION





Basu, Narasimha 1999, *JFM*

EQUATIONS FOR A 'BOUSSINESQ CLOUD'

$$\nabla \cdot \boldsymbol{u} = 0,$$

(mass)

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} - \boldsymbol{g}\alpha T,$$

(momentum)

$$\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)T = \kappa \nabla^2 T + \frac{J}{\rho\, c_p} \mathrm{H}$$

(energy)

Basu, RN 1999 *J. Fluid Mech.*

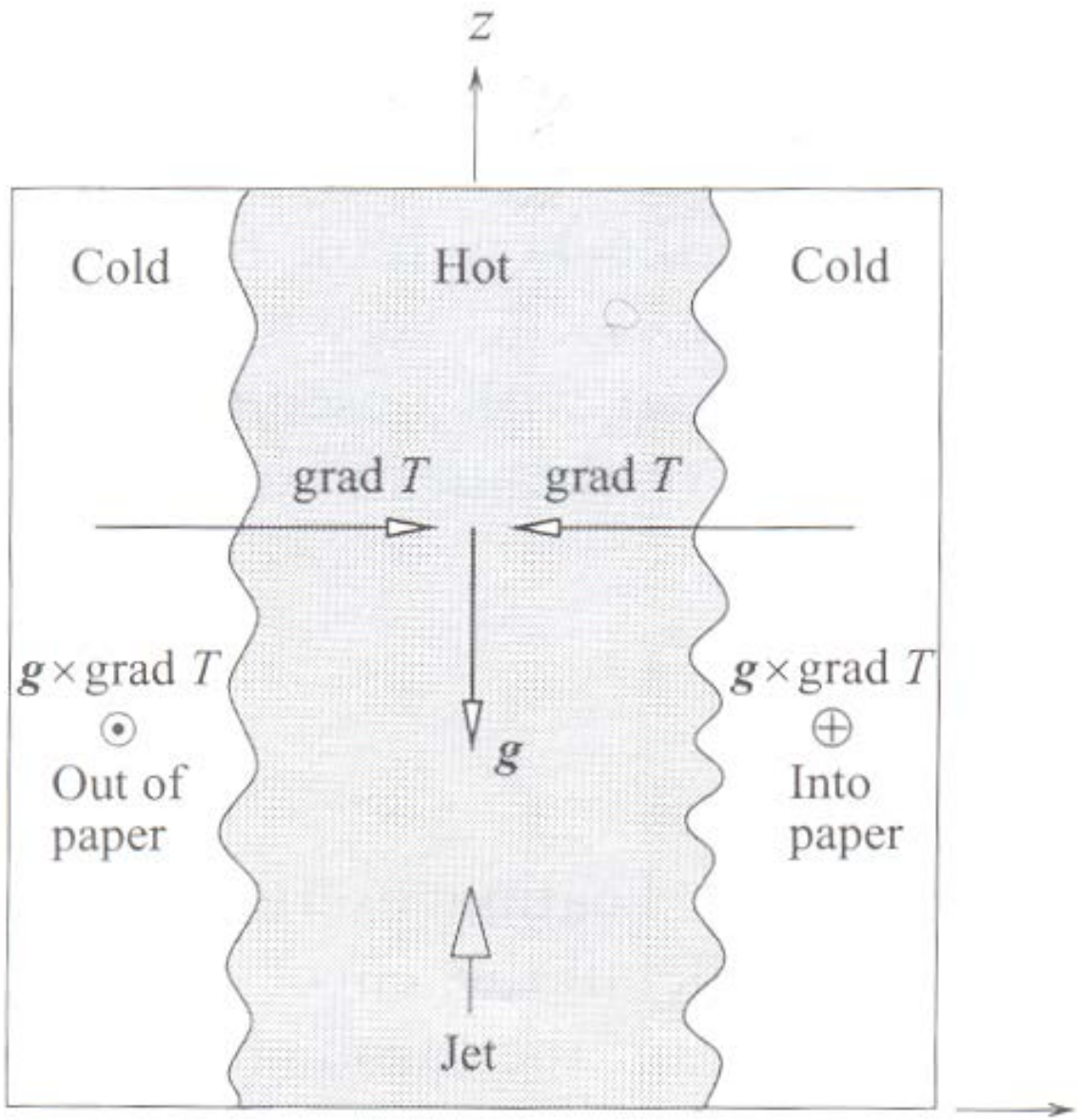
VORTICITY IN BOUSSINESQ CLOUD

$$\underbrace{\frac{\partial \boldsymbol{\omega}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{\omega}}_{\text{advect}} \underbrace{- (\boldsymbol{\omega}\cdot\nabla)\boldsymbol{u}}_{\text{tilt, stretch}} \underbrace{- \nu\nabla^2\boldsymbol{\omega}}_{\text{diffuse}} = \underbrace{\alpha \boldsymbol{g} \times \nabla T}_{\text{create}}$$

$$\left.\begin{aligned} \boldsymbol{u}(\boldsymbol{x},t) &= \boldsymbol{u}(\boldsymbol{x}+L\mathbf{e}_i,t), \quad & p(\boldsymbol{x},t) &= p(\boldsymbol{x}+L\mathbf{e}_i,t), \\ T(\boldsymbol{x},t) &= T(\boldsymbol{x}+L\mathbf{e}_i,t), & i &= 1,2,3. \end{aligned}\right\}$$

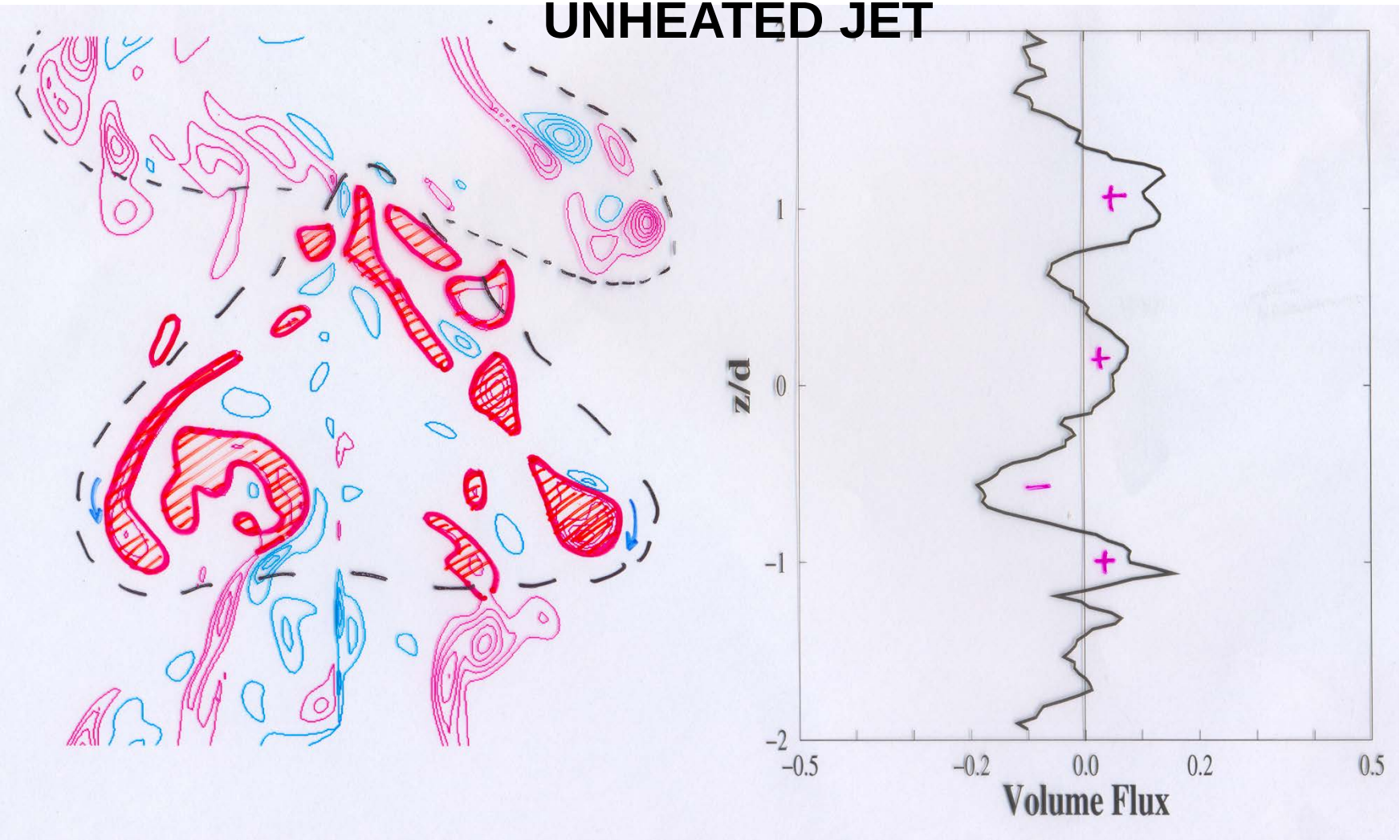
Basu, RN 1999 *J. Fluid Mech.*

CREATING VORTICITY BY BAROCLINIC TORQUE



Basu, RN 1999 *J. Fluid Mech.*

COHRERENT STRUCTURE IN AZIMUTHAL VORTICITY



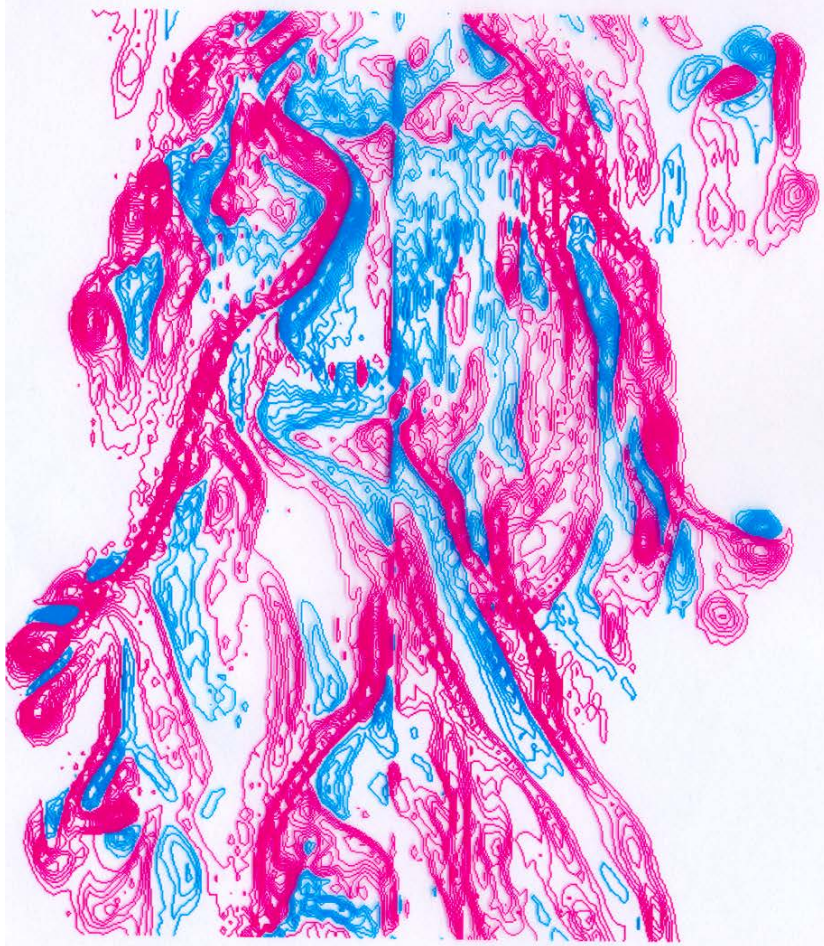
t = 35, x = 65

Volume flux vs. z/d at t = 35

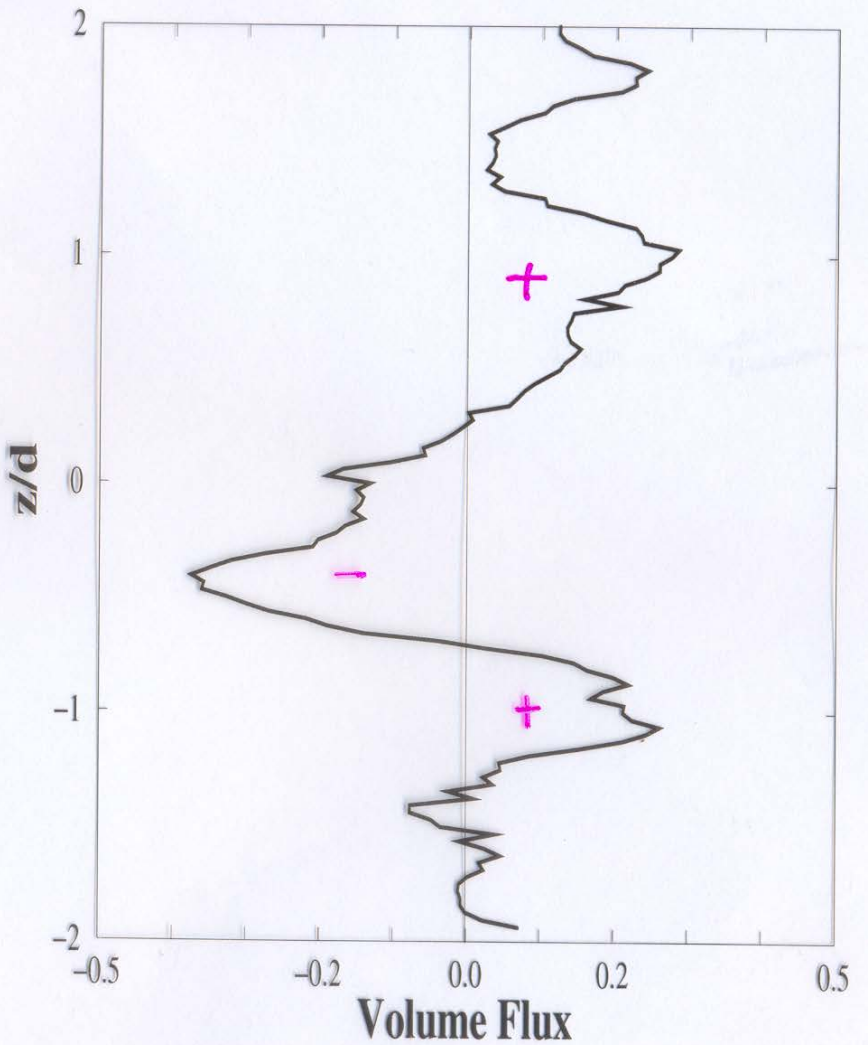
RN, Shivakumar 1999 IUTAM Goettingen

AZIMUTHAL VORTICITY

FULLY HEATED JET



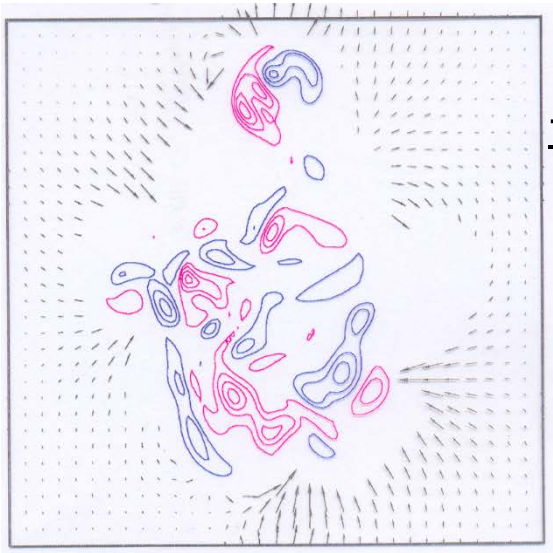
t = 35, x = 65



Volume flux vs. z/d at t = 35

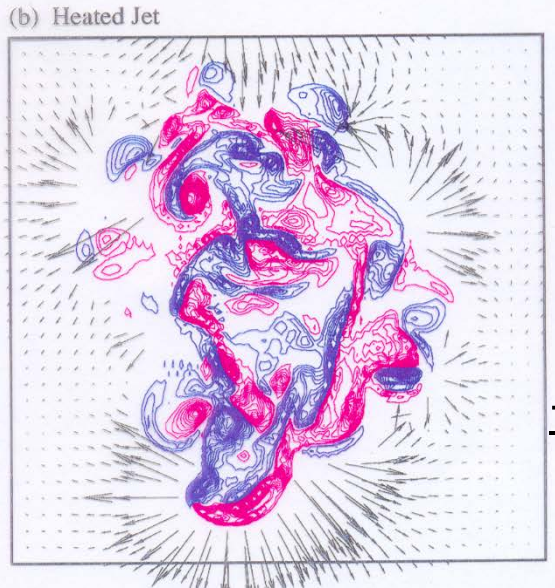
RN, Shivakumar 1999 IUTAM Goettingen

UNHEATED, HEATED JETS

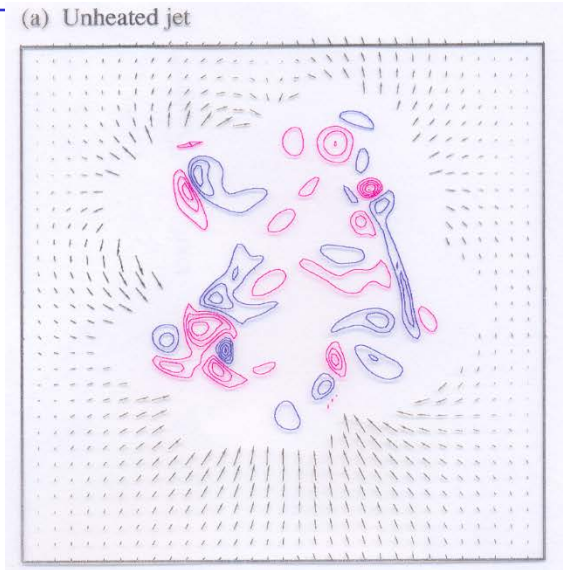


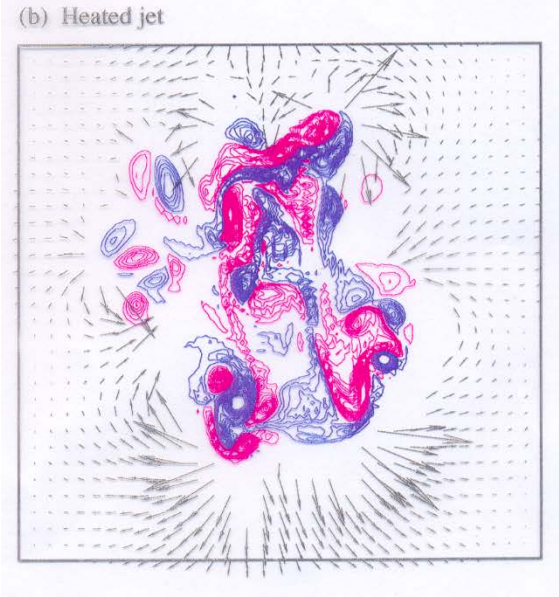
$\pm\ \omega_z$: 0.2(0.2)3

Section at Widest Station



$\pm\ \omega_z$: 0.5(0.5)10

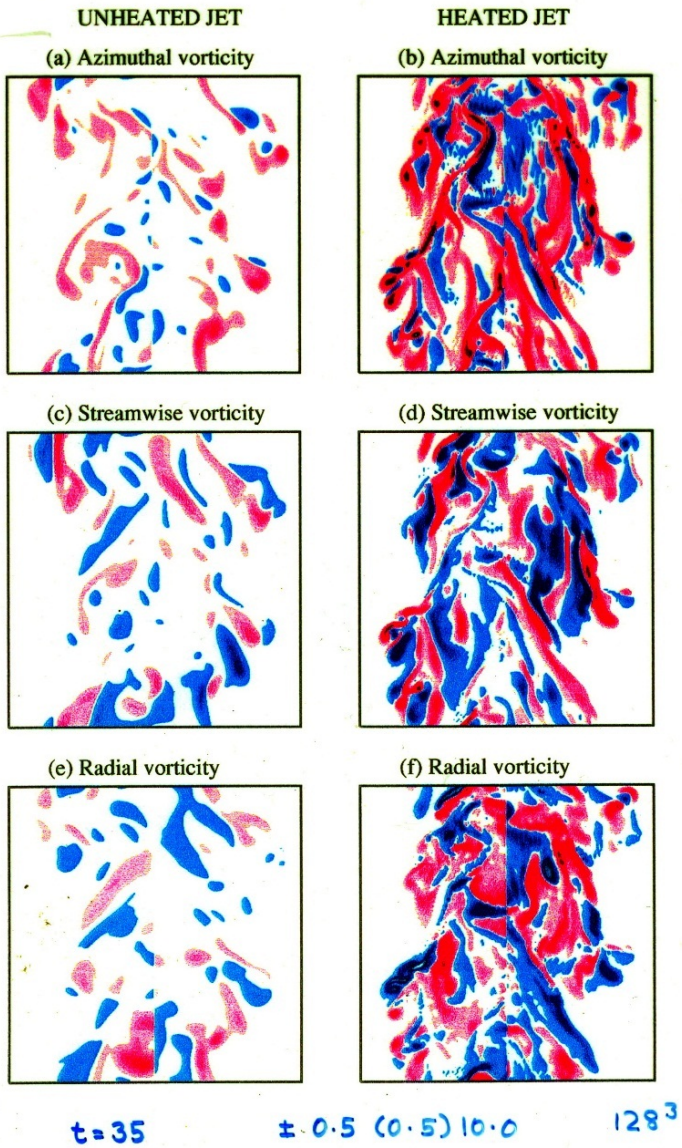




Section at Narrowest Station

RN, Bhat 2008

VORTICITY DISTRIBUTIONS



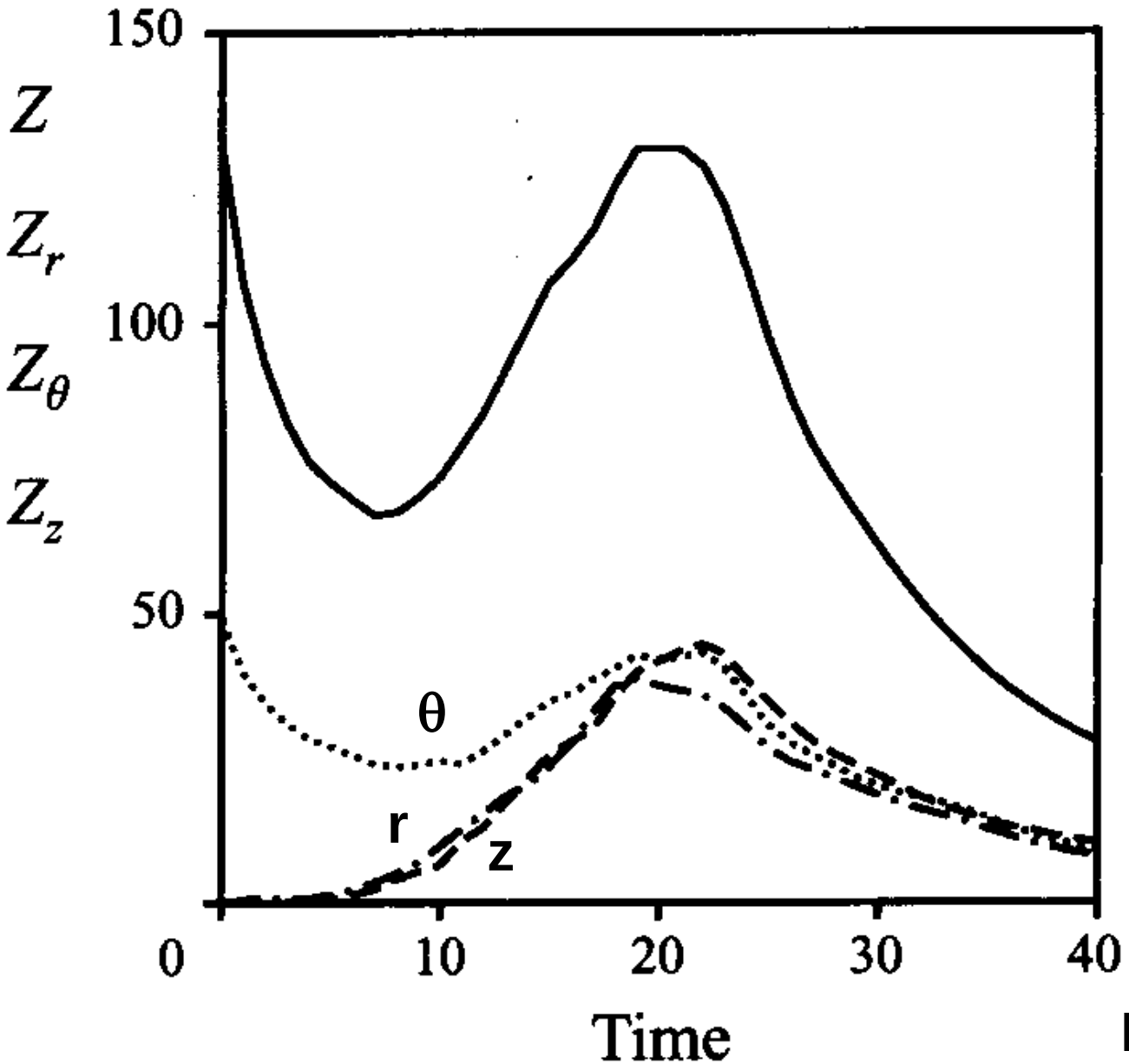
Left: Ordinary (Unheated), Right: Cloud (Heated)

Azimuthal

Axial

Radial

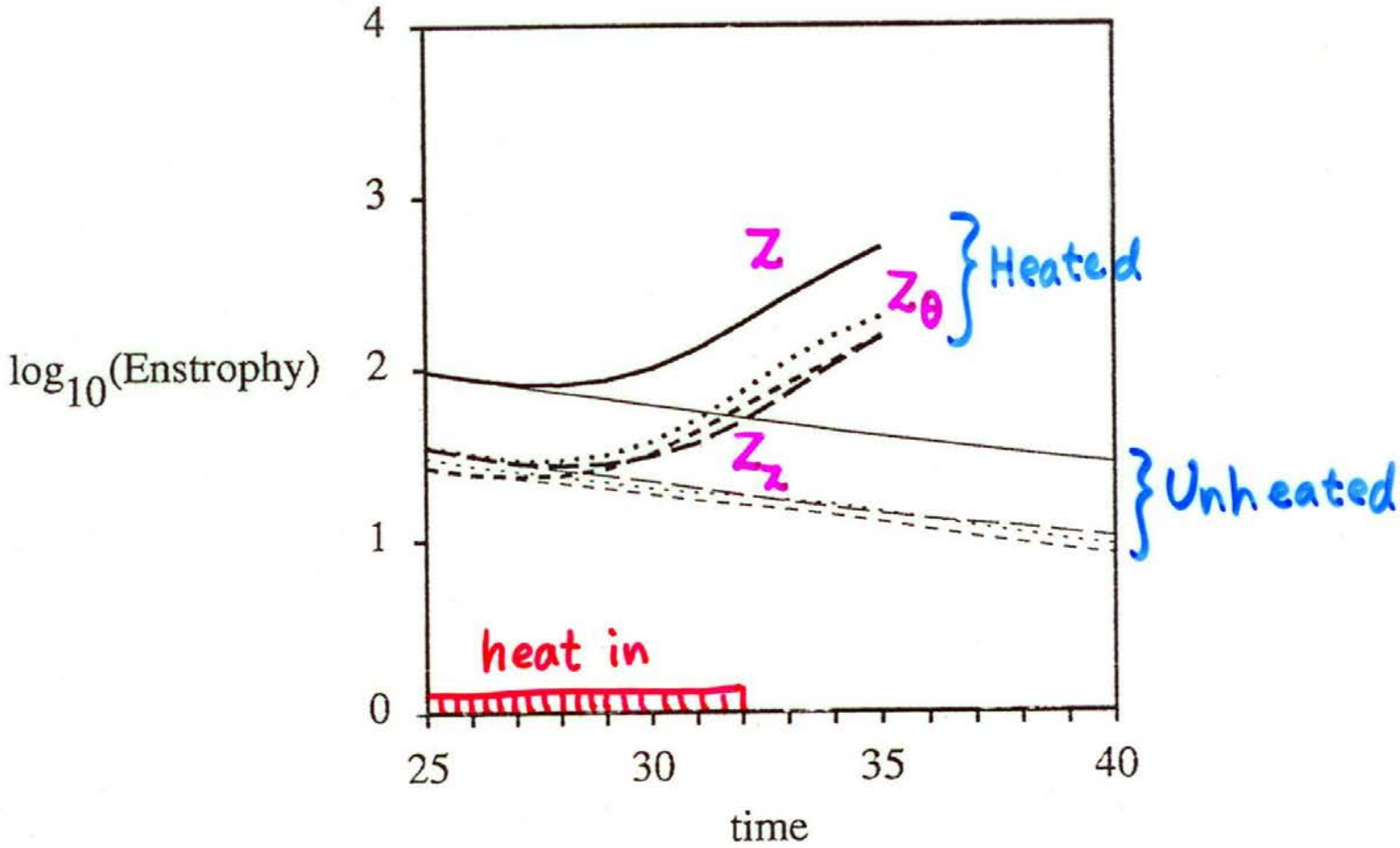
ENSTROPHY IN ORDINARY JET



Enstrophy = mean squared fluctuating vorticity

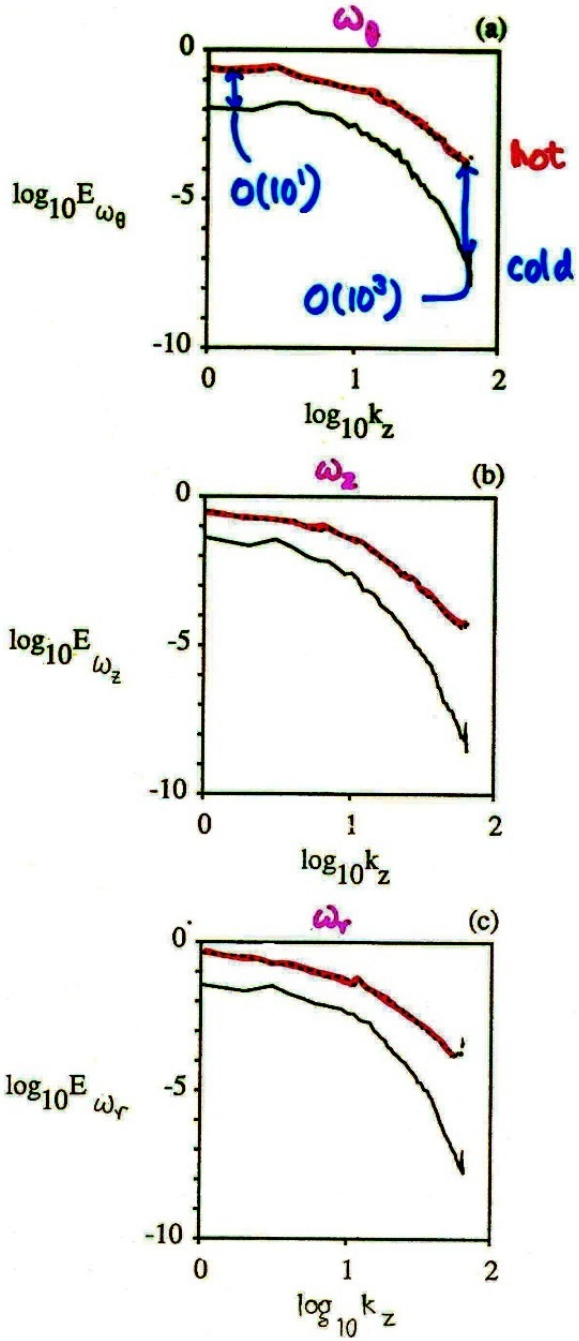
Basu, RN 1999 *JFM*

ENSTROPHY INCREASE WITH HEATING



Basu, RN 99, *JFM*

ENSTROPHY SPECTRA

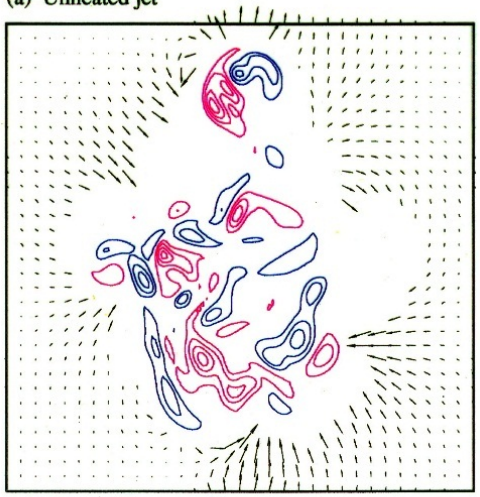


DIAMETRAL SECTIONS

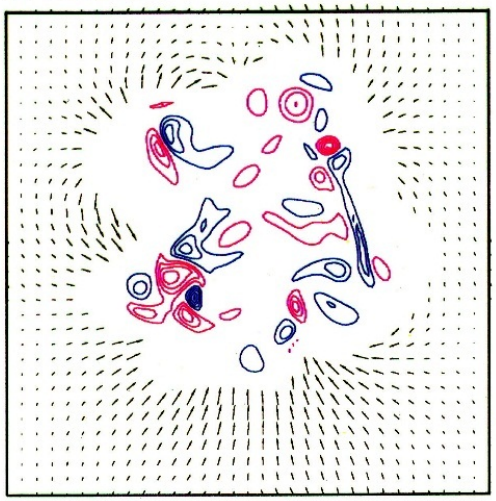
SECTION AT WIDEST STATION

SECTION AT NARROWEST STATION

(a) Unheated jet

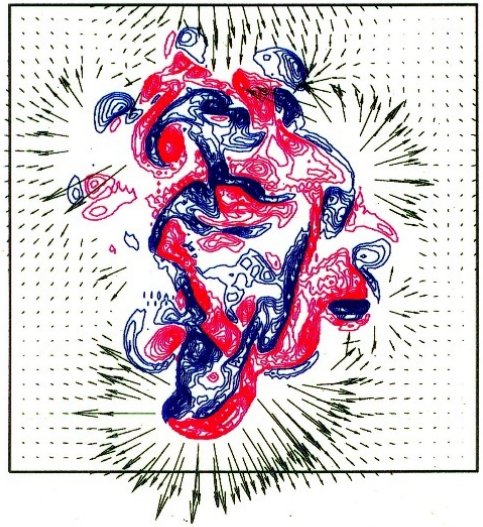


(a) Unheated jet

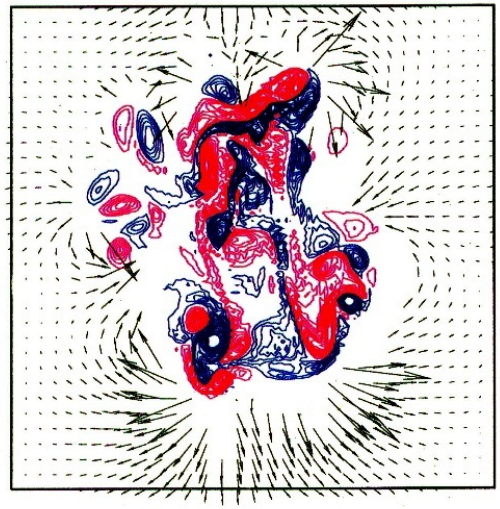


$\pm\ \omega_z : 0.2(0.2)3$

(b) Heated Jet



(b) Heated jet



$\pm\omega_z : 0.5\ (0.5)\ 10$

TRANSIENT DIABATIC PLUME

Megha 3

Prasanth++ 2014

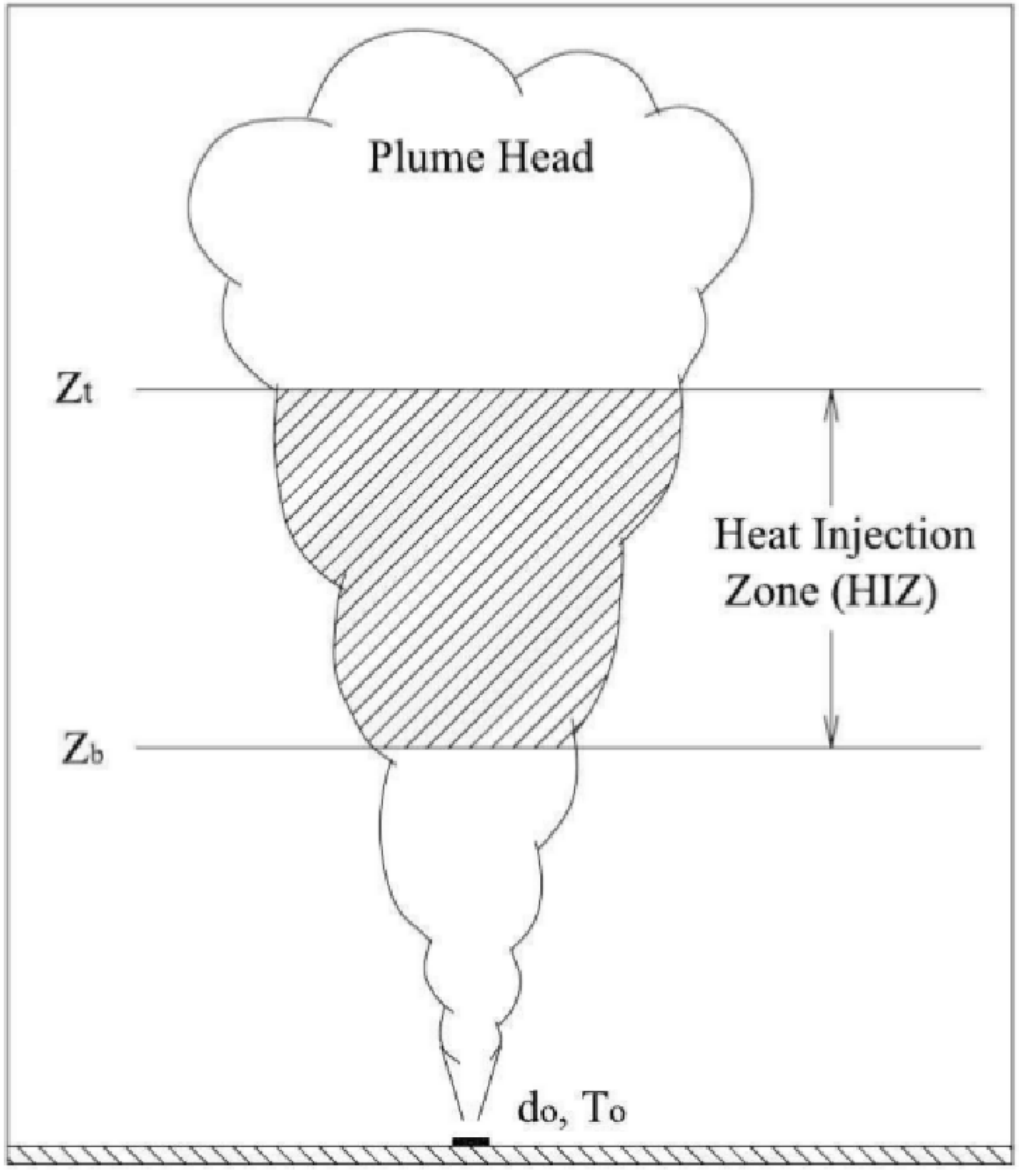
Flow Configuration

- $\mathbf{d_o}$ - diameter of the source patch

- T_o - source temperature above the ambient

- Z_b and Z_t – vertical extent of the HIZ

- Horizontal extent of the HIZ is defined by a passive scalar (threshold value ~ 10^{-4}) .



AN EXPLORATORY NUMERICAL EXPERIMENT

Direct Navier-Stokes-Boussinesq

- Reynolds number: 2000.
- Fractional-step method is used to solve the governing equations.
- Non-uniform grid, size 129 x 10^6.
- Poisson solver: Preconditioned (multi-grid based) GMRes.

NUMERICAL PARAMETERS

Exploratory runs

- Domain Size: 40 x 40 x 40 (x y z)
- Grid : 128 x 128 x 256 ~ 4 x 10^6 cells

Resolved Simulation

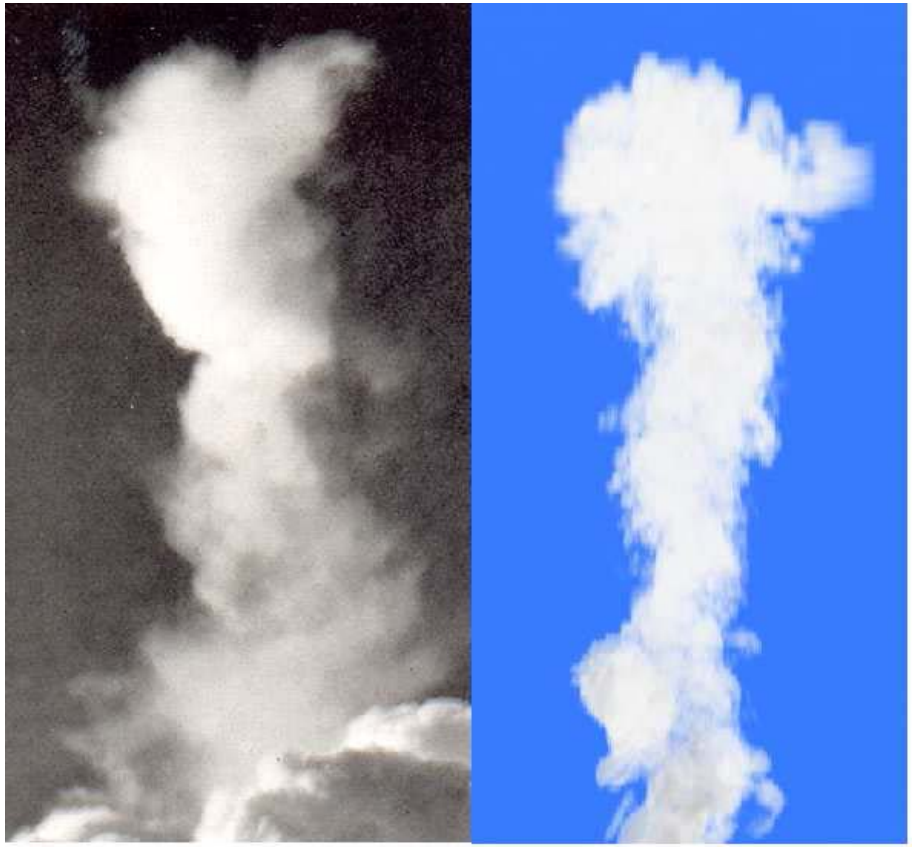
- Domain Size: 70 x 70 x 39.9 (x y z)
- Grid : 402 x 402 x 798 ~ 129 x 10^6 cells

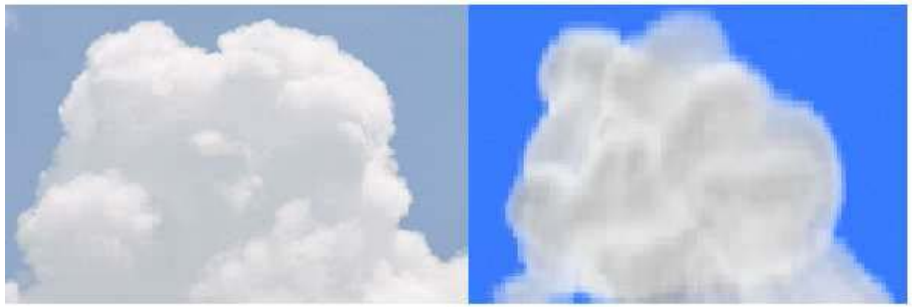
Common parameters

- Reynolds No : 2000
- 10% noise added to the temperature source (z = 0)

COMPARISON OF CLOUD SHAPES

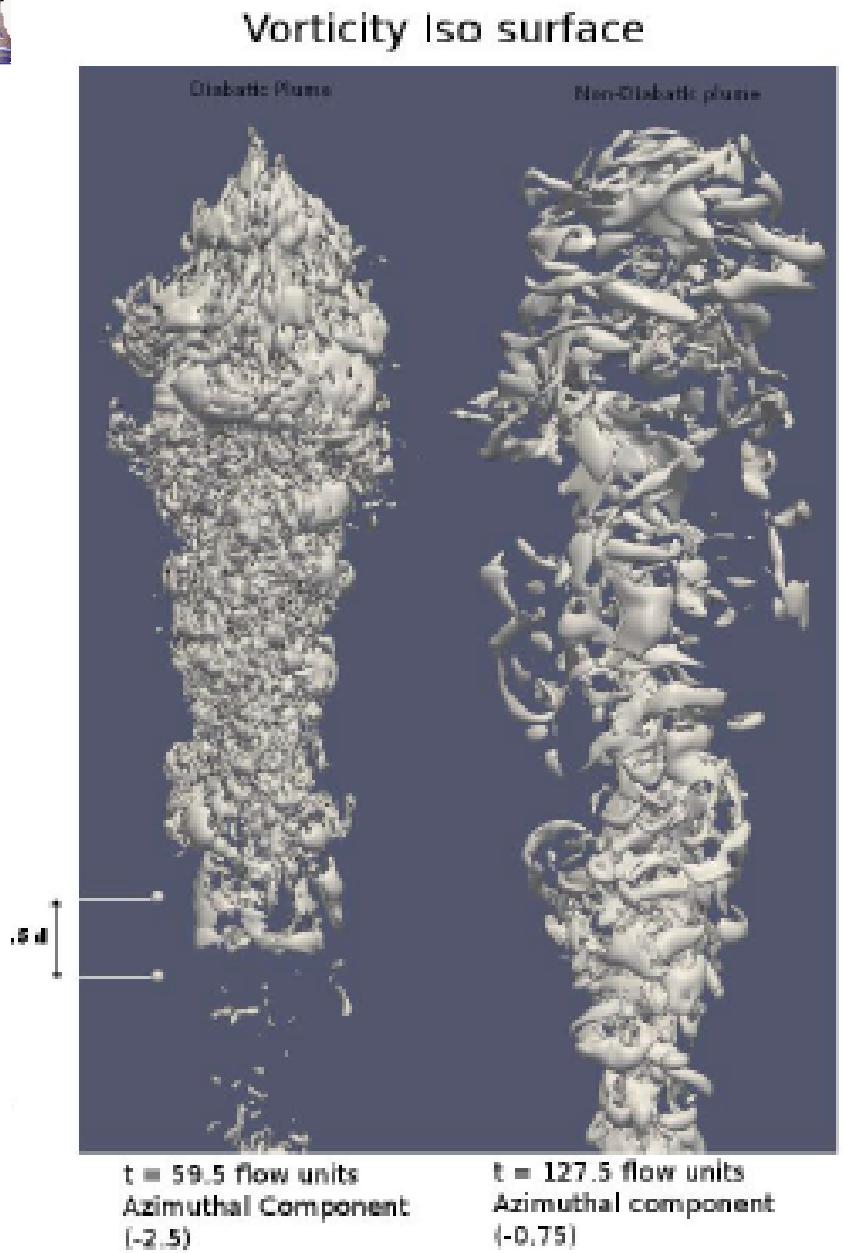
Real **Cyber**





- Re = 2000
- Pr = 1.0
- $\Delta t = 0.005$
- Grid: 128 x 128 x 256
- HIZ: $Z_b = 10d$, $Z_t = 15d$
- Volumetric visualisation using PARAVIEW.

VORTICITY EXPLODES WITH HEATING



Left: With heating, iso-surface at 2.5

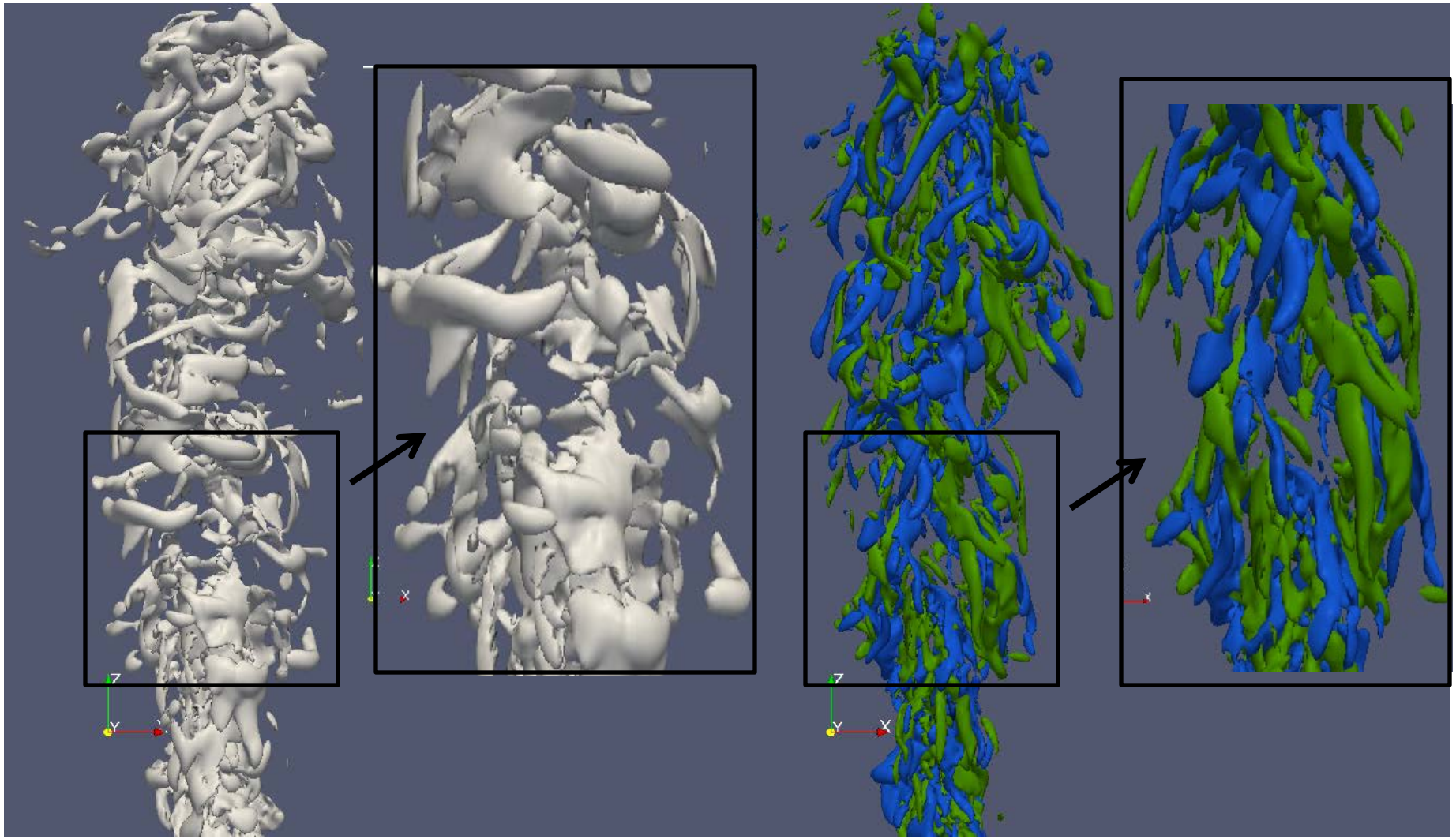
Right: No heating , iso-surface at 0.75

Baroclinic torque spins up cloud

Vorticity iso surface for plumes

Azimuthal component (-1.0)

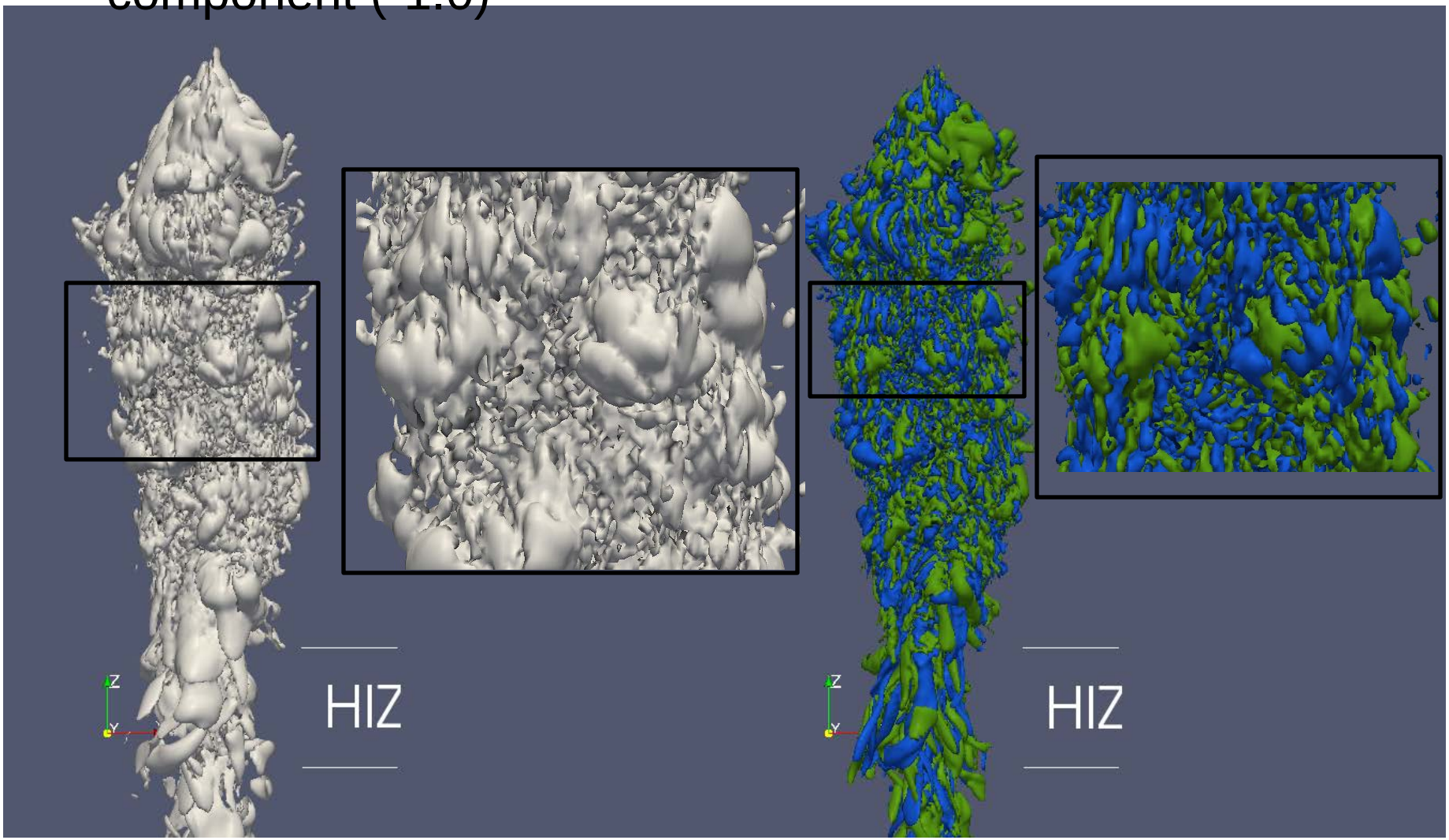
Axial component (-1.0 blue, +1.0 green)



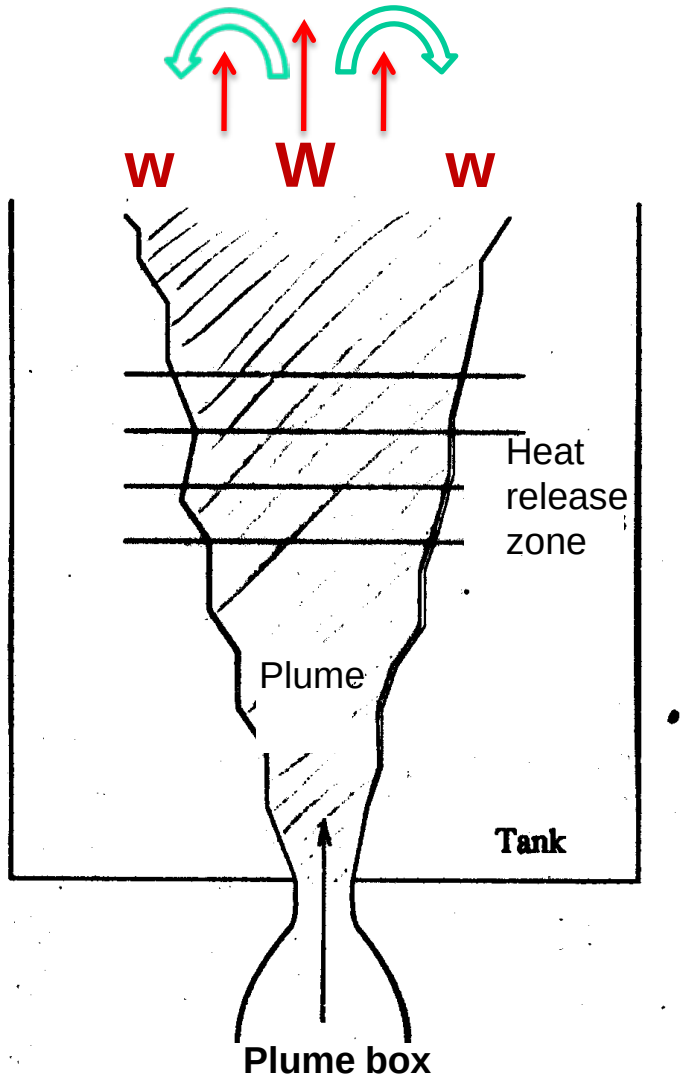
Vorticity iso surface for cloud flow

Azimuthal component (-1.0)

Axial component (-1.0 blue, 1.0 green)



HOW THE BAROCLINIC TORQUE WORKS



The Baroclinic Torque

The varying buoyancy force

Temperature gradient

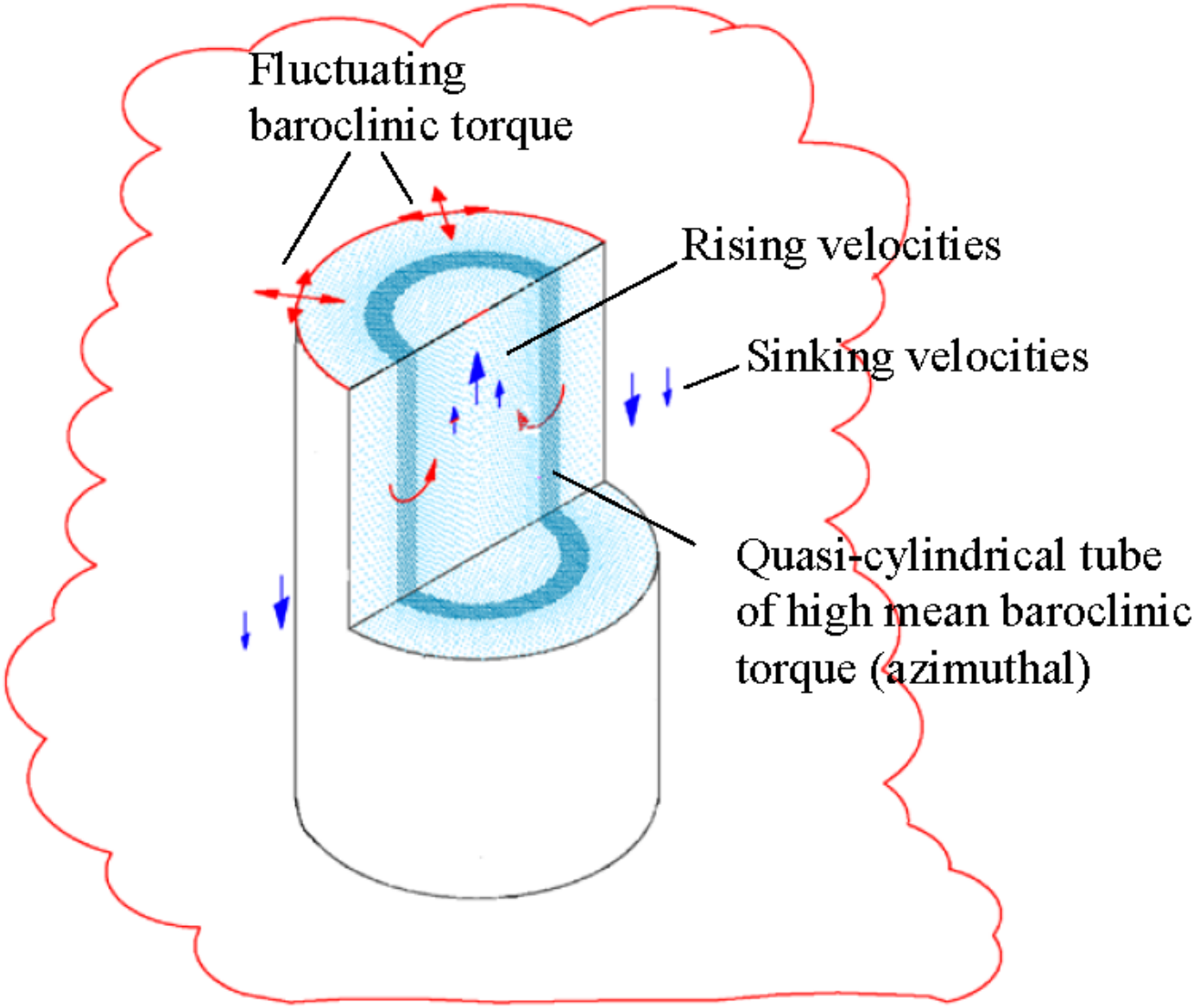
The baroclinic torque is proportional to the temperature gradient, so is a maximum mid-way between cloud centre and edge

There is a quasi-cylindrical tube of maximum baroclinic torque embedded within the cloud flow

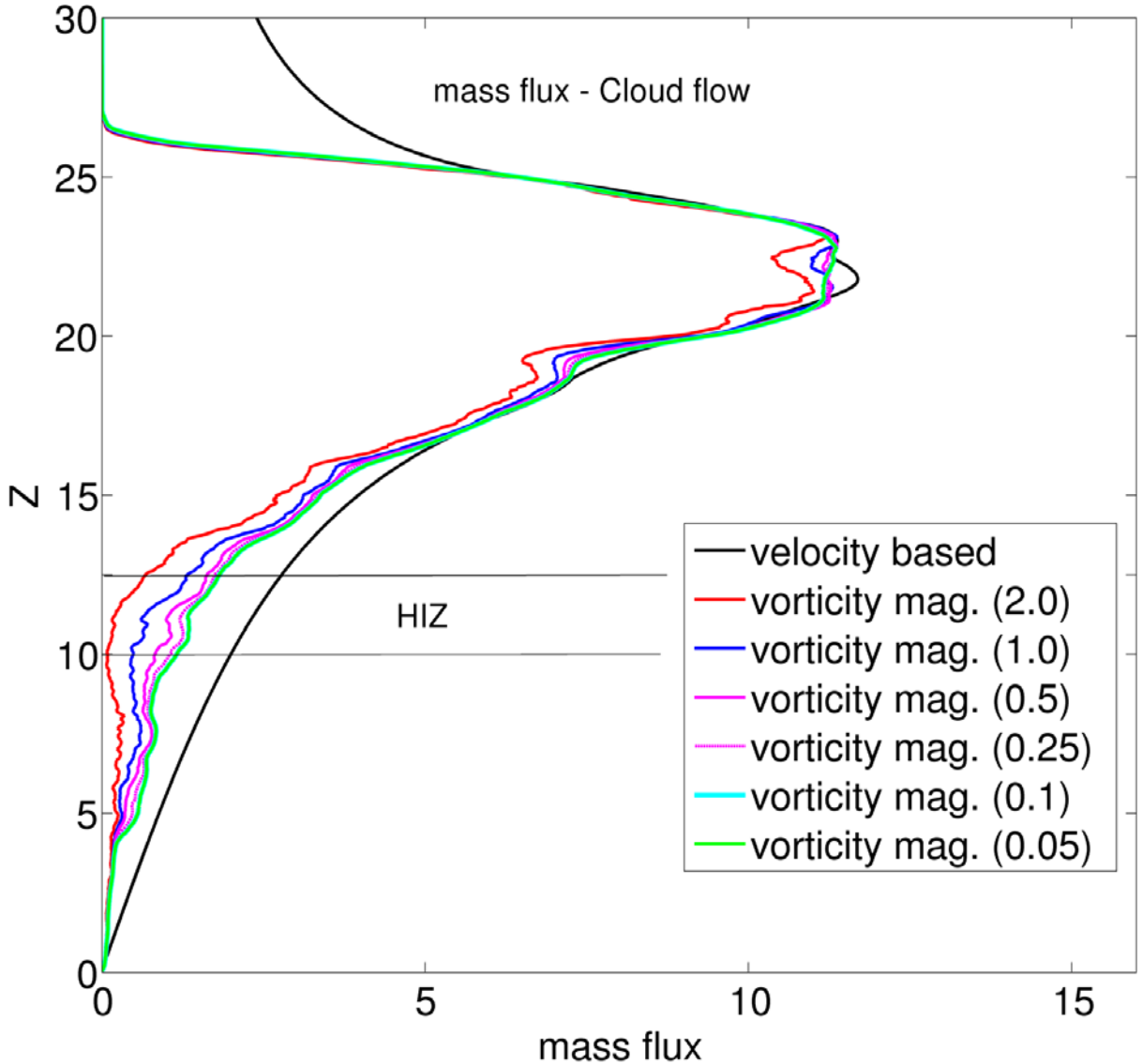
The fluctuating baroclinic torque is a huge source of small-scale vorticity. Could that be what makes some cumulus clouds so crinkly at the edges ?

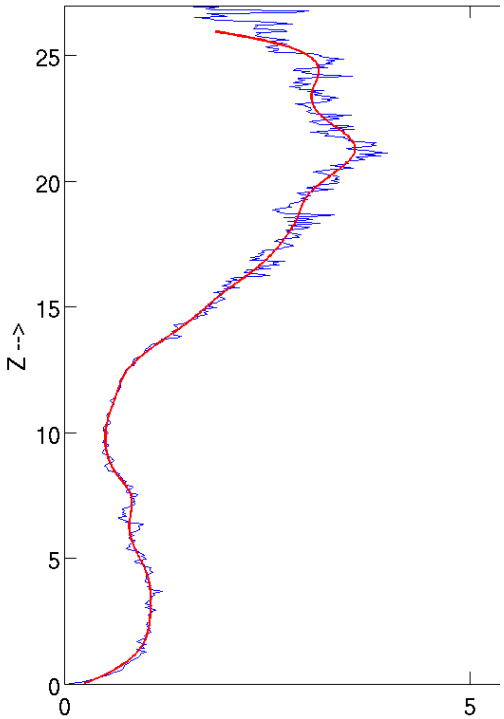
RN 2012

HOW THE BAROCLINIC TORQUE WORKS



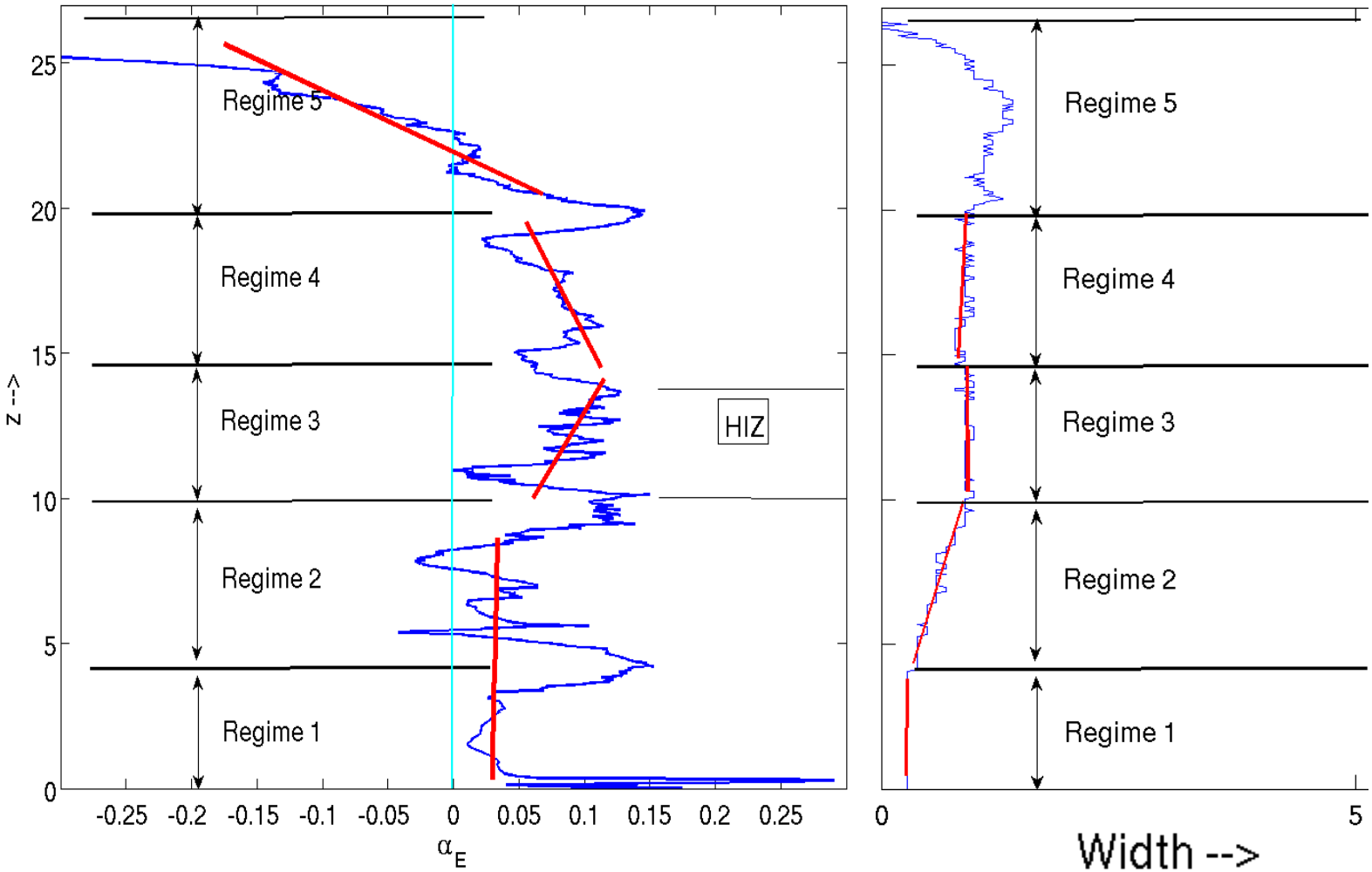
WHAT IN-CLOUD MASS FLUX ?





Prasanth ++ 2016

Entrainment coefficient and width

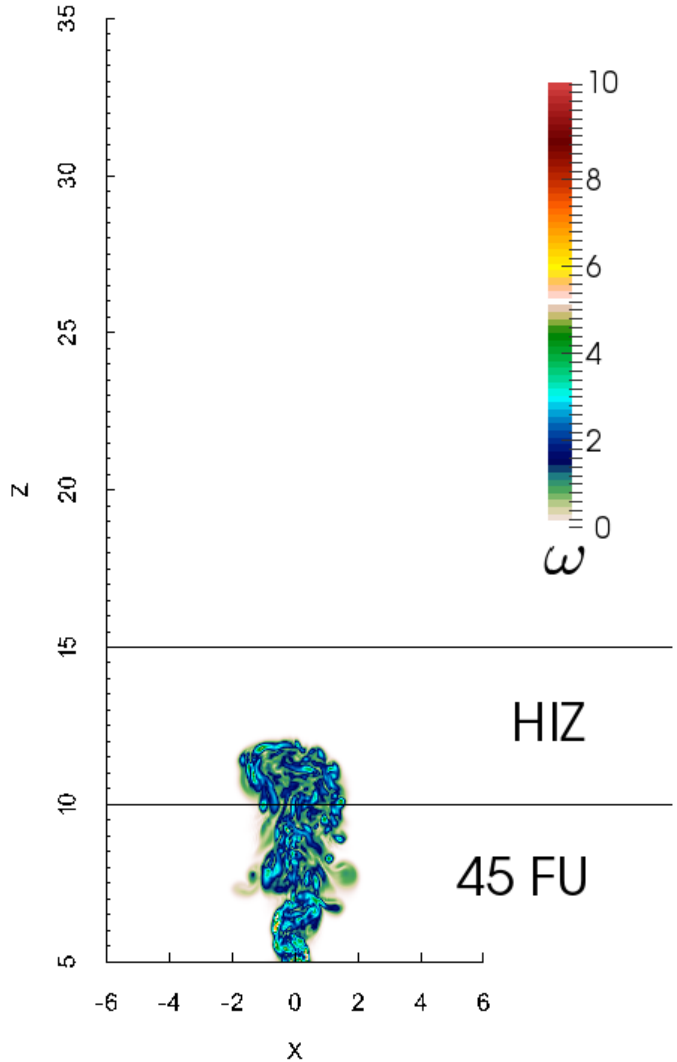


EVOLUTION OF A T.D.P.

Re = 2000
Totally 90 FU
HIZ : 10 – 15 diameters
Heating stops at 65 FU

Samrat Rao++ 2016

Axial sections at $y = 0$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10
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-2
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4
6
x
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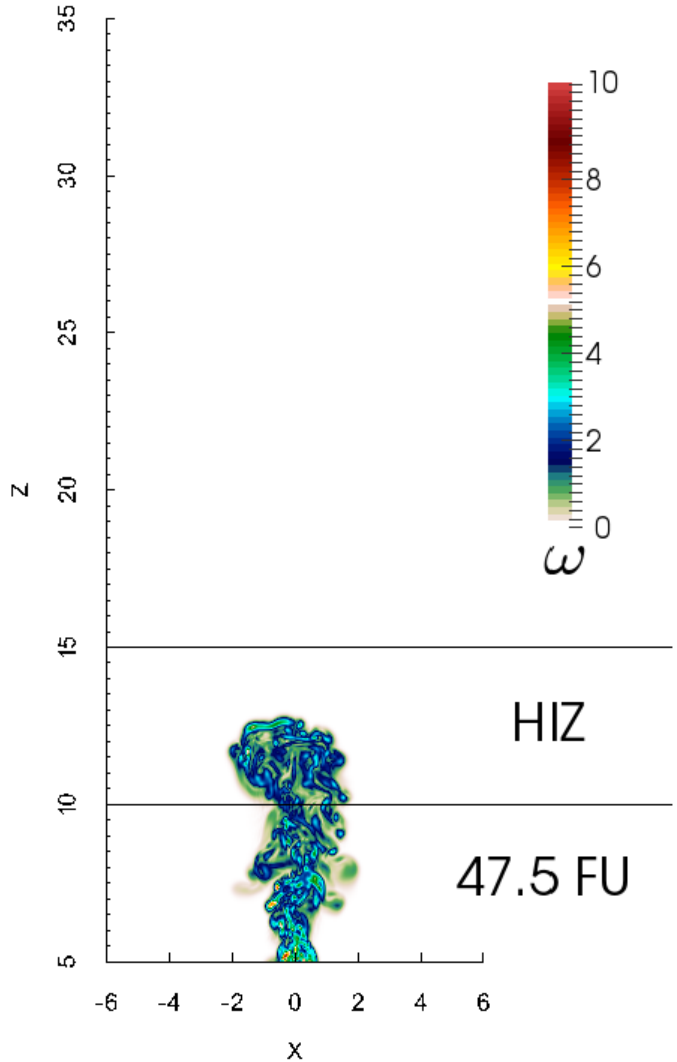
8
6
4
2
0
ω
HIZ
45 FU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x
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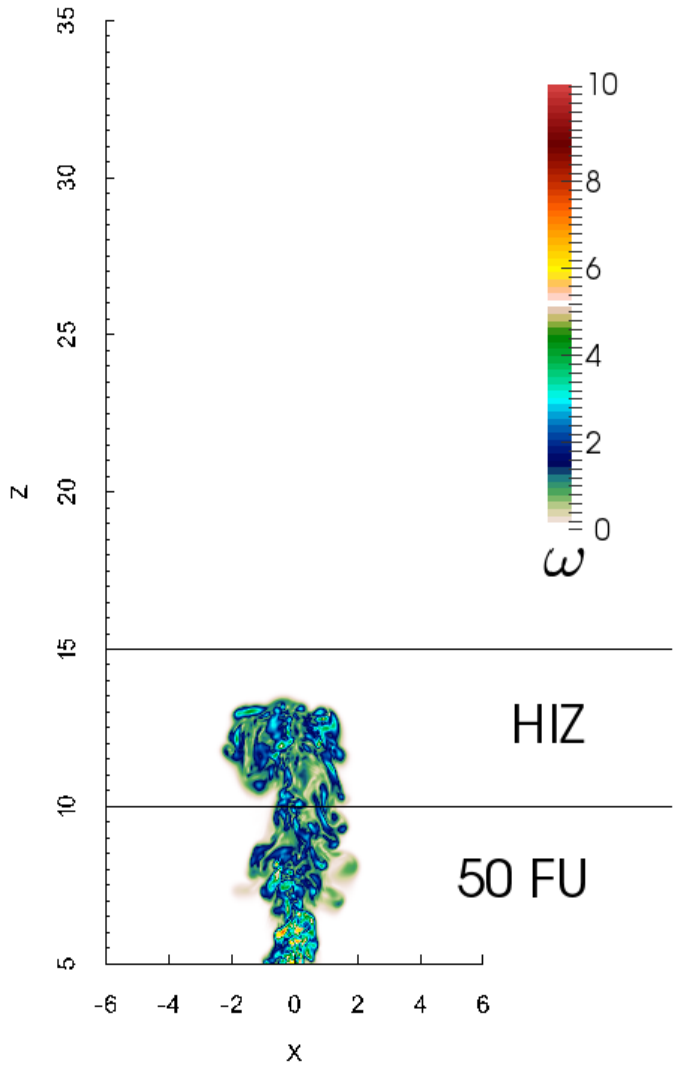
8
6
4
2
0
ω
HIZ
47.5 FU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30
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x
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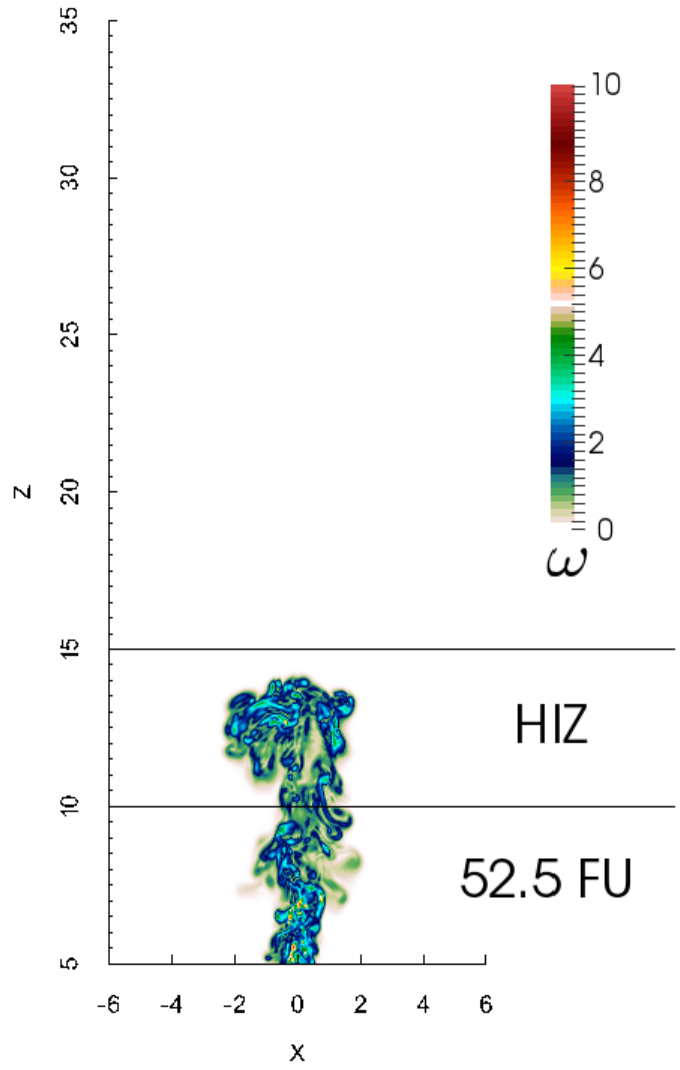
8
6
4
2
0
ω
HIZ
50 FU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4
6
x
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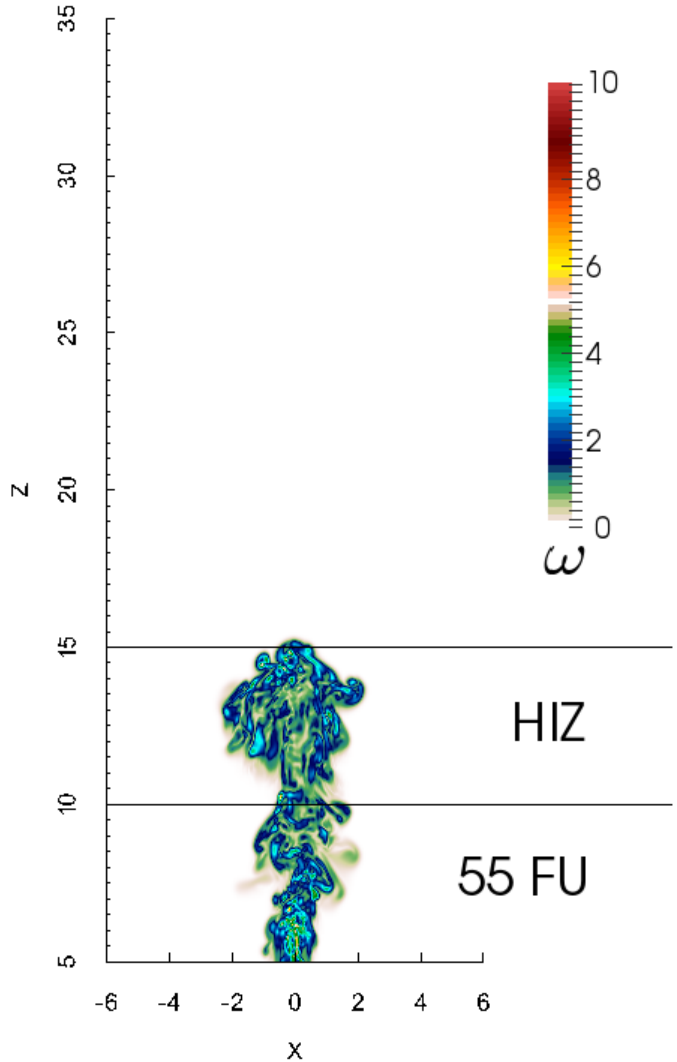
8
6
4
2
0
ω
HIZ
52.5 FU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0
2
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6
x
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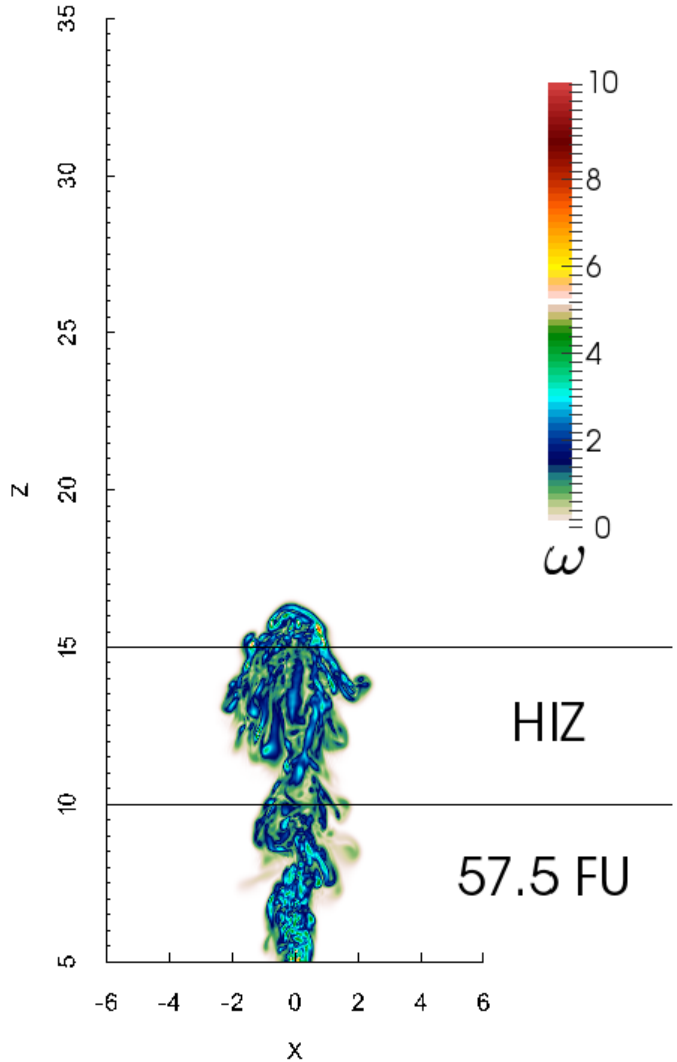
8
6
4
2
0
ω
HIZ
55 FU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0
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4
6
x
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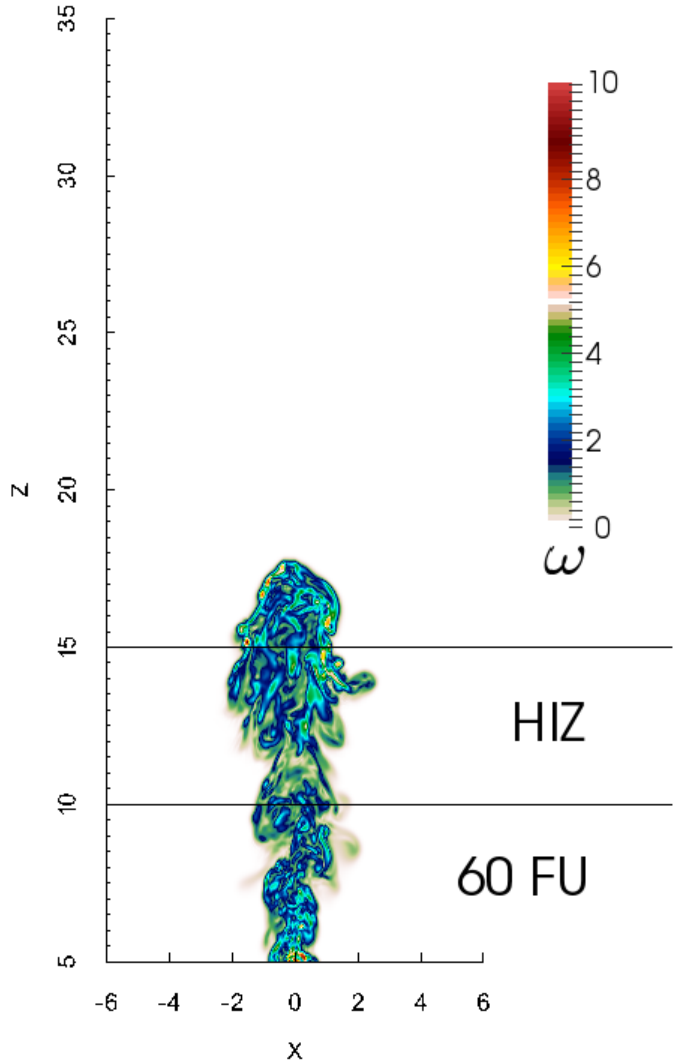
8
6
4
2
0
ω
HIZ
57.5 FU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x
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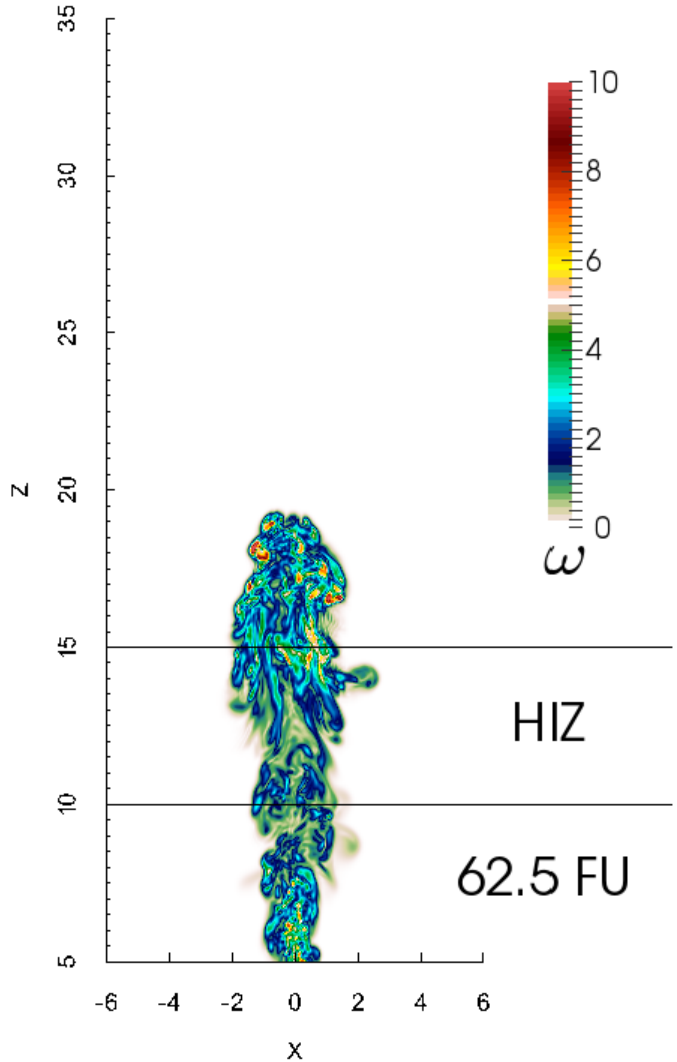
8
6
4
2
0
ω
HIZ
60 FU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6
x
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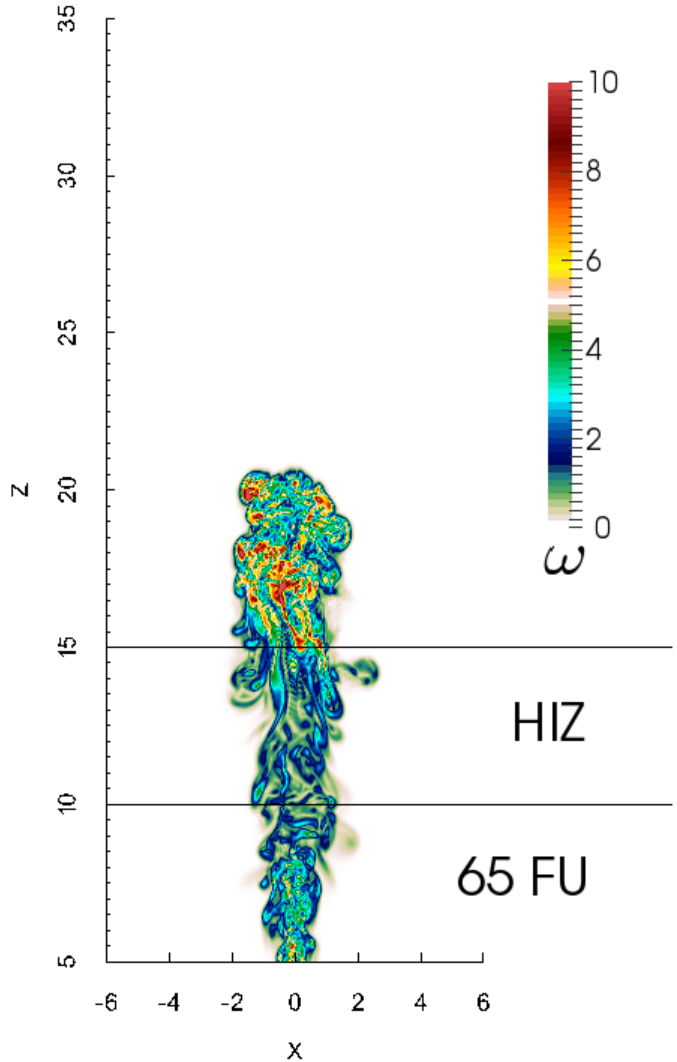
8
6
4
2
0
ω
HIZ
62.5 FU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4
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x
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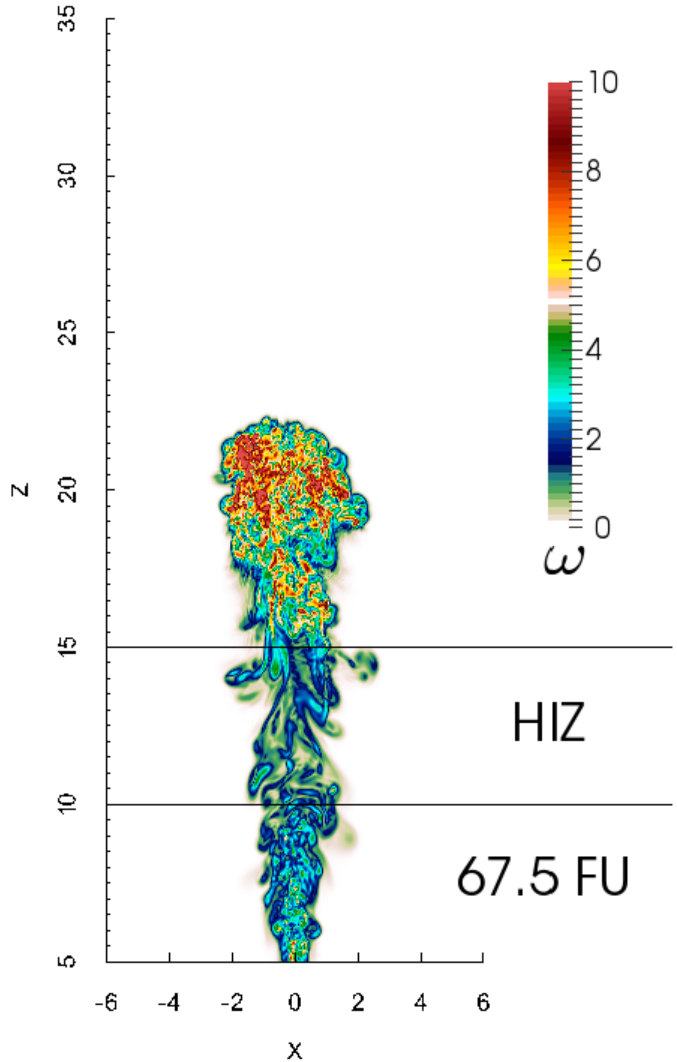
8
6
4
2
0
ω
HIZ
65 FU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x
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8
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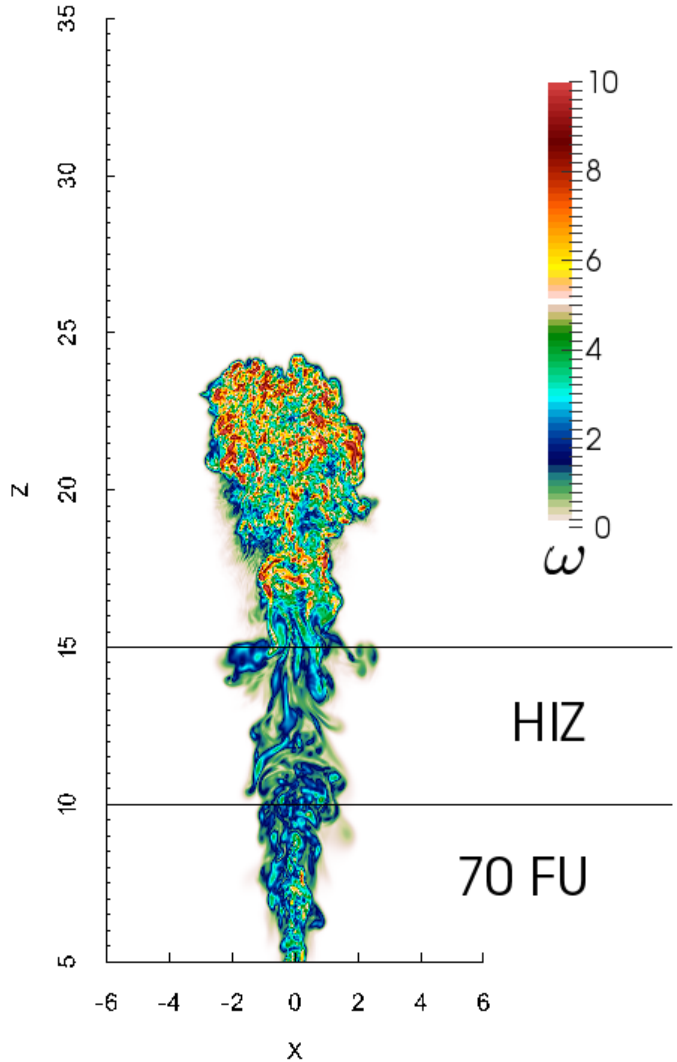
4
2
0
ω
HIZ
67.5 FU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4
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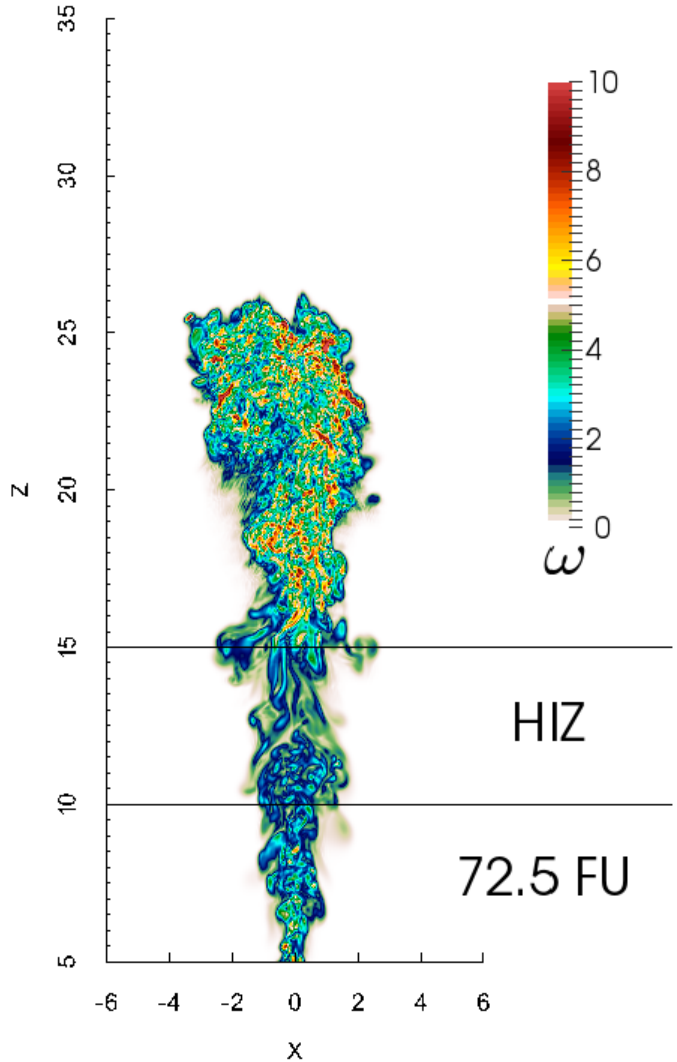
0
ω
HIZ
70 FU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x
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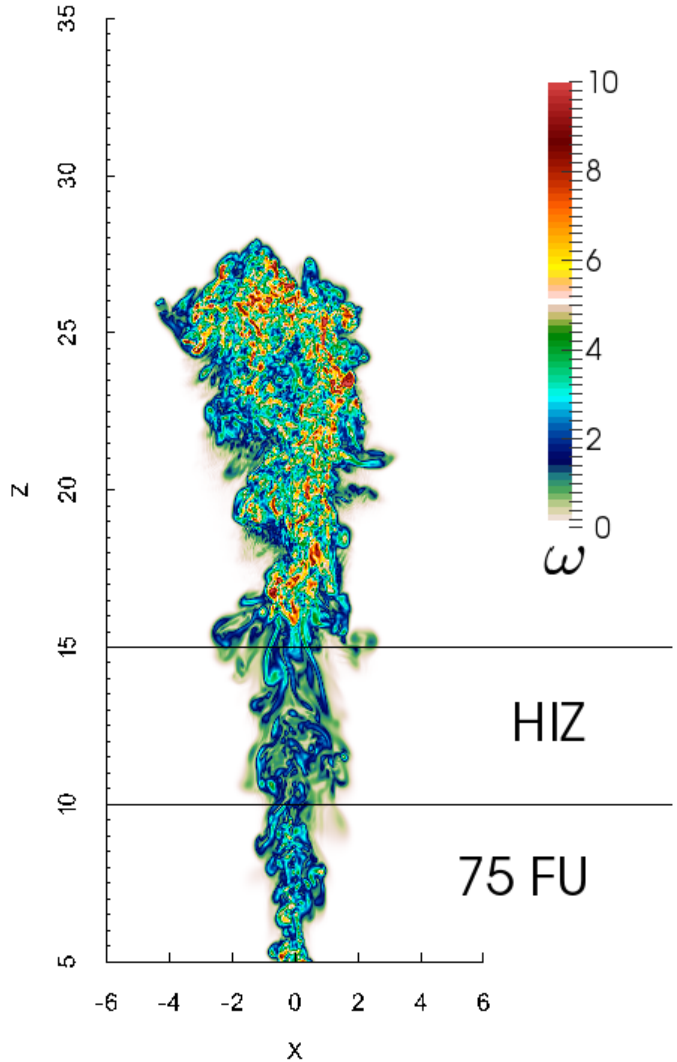
8
6
4
2
0
ω
HIZ
72.5 FU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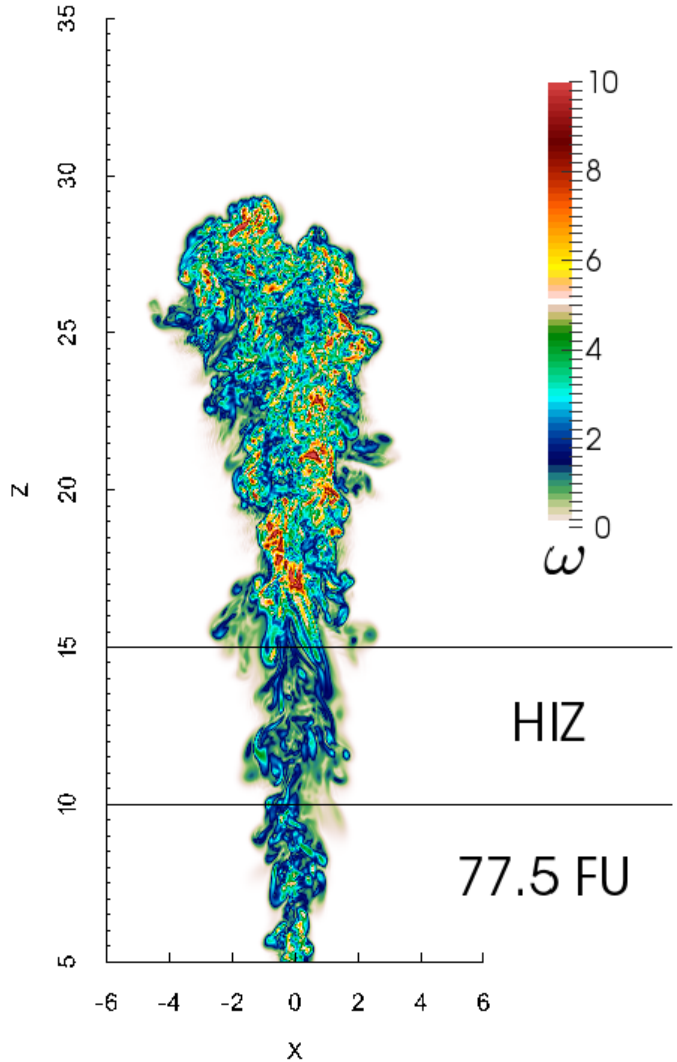
4
6
x
10
8
6
4
2
0
ω
HIZ
75 FU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z
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0
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x
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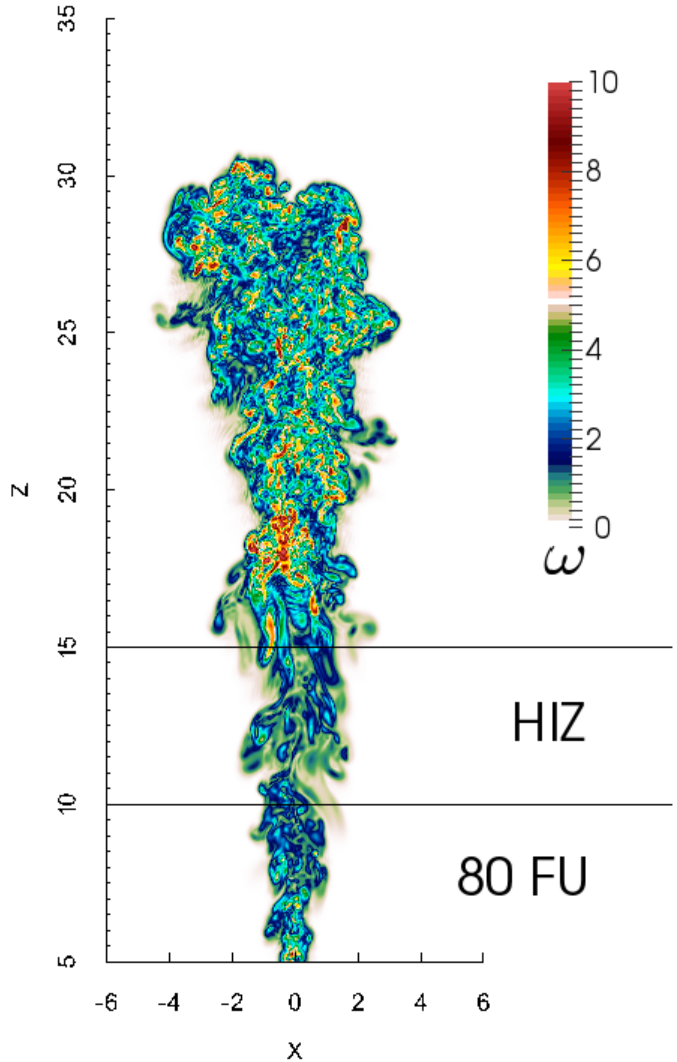
8
6
4
2
0
ω
HIZ
77.5 FU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6
x
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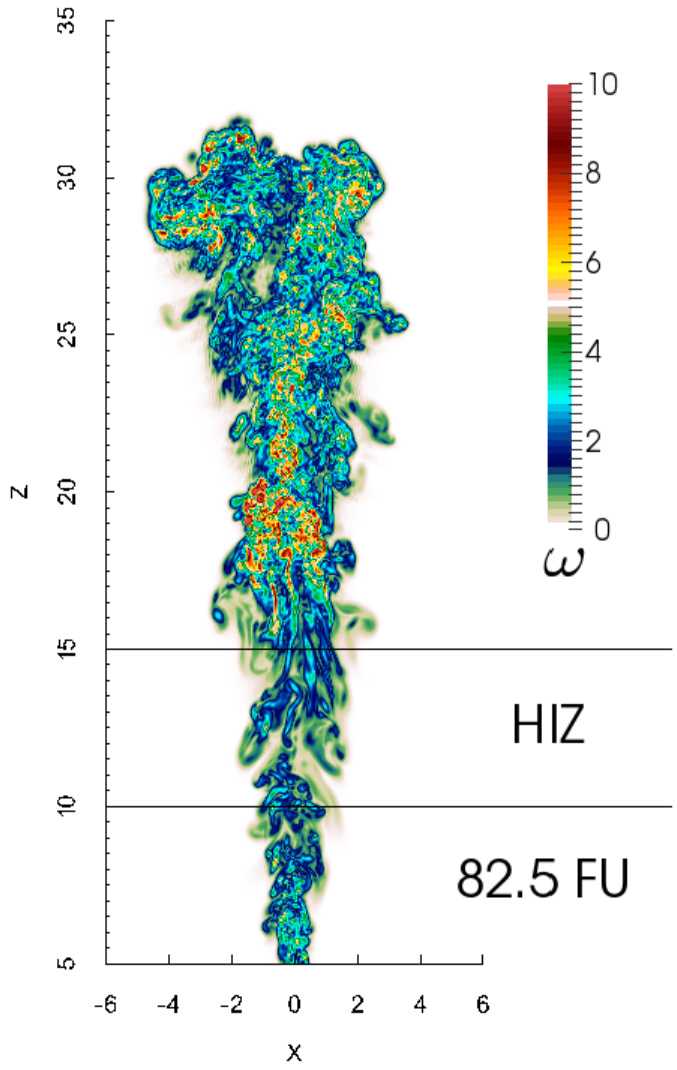
6
4
2
0
ω
HIZ
80 FU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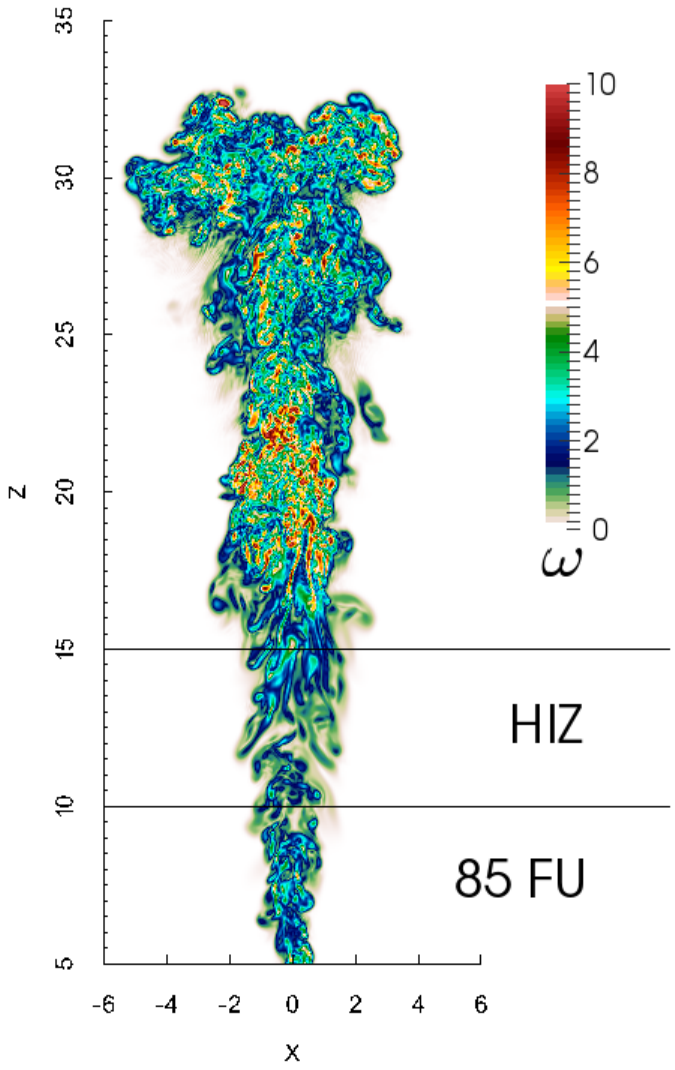
x
10
8
6
4
2
0
ω
HIZ
82.5 FU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2
4
6
x
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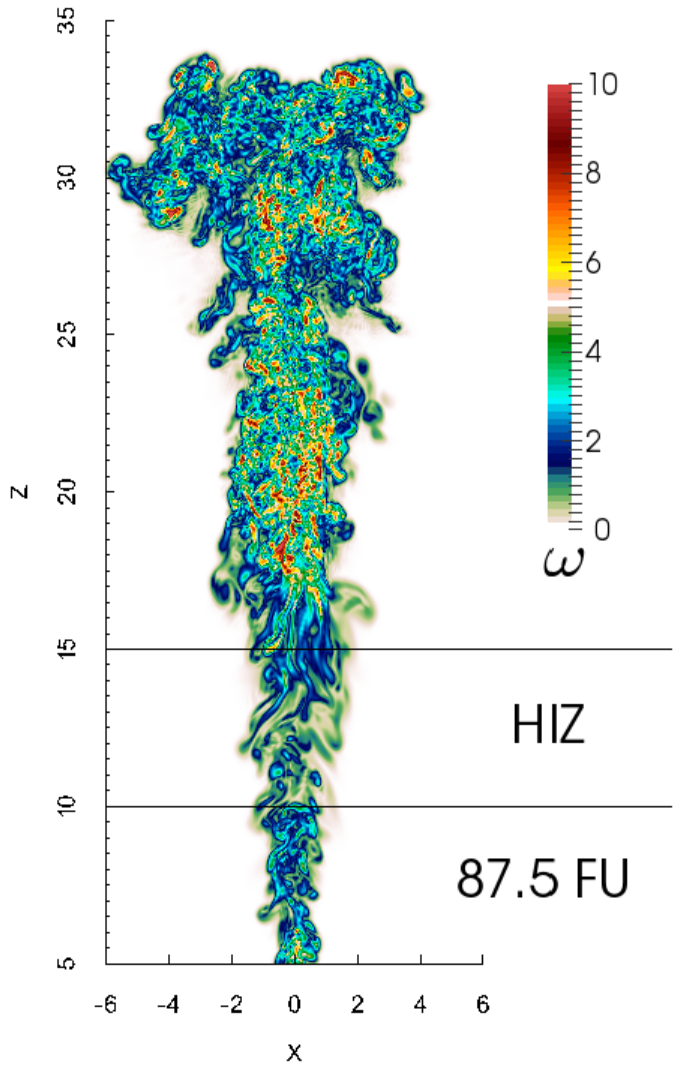
8
6
4
2
0
ω
HIZ
85 FU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15
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z
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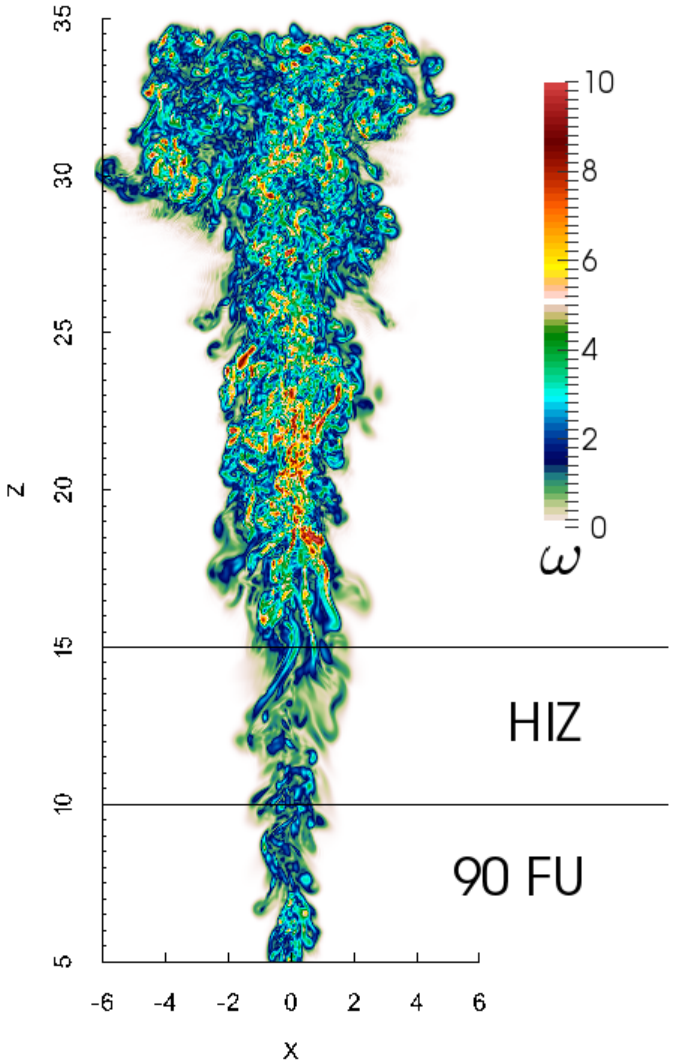
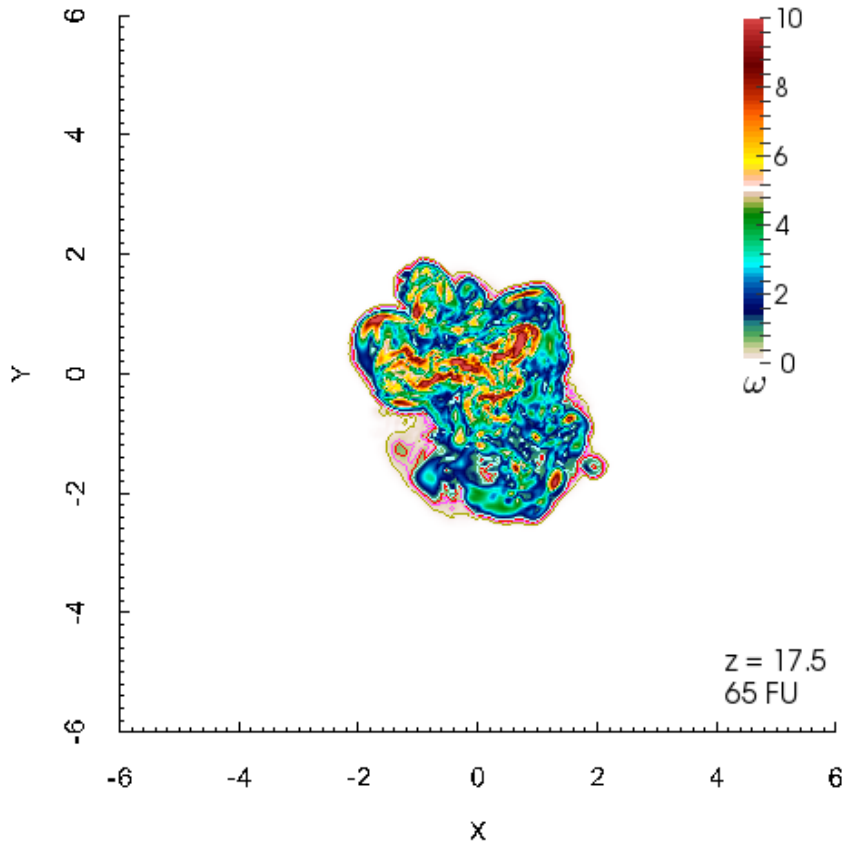
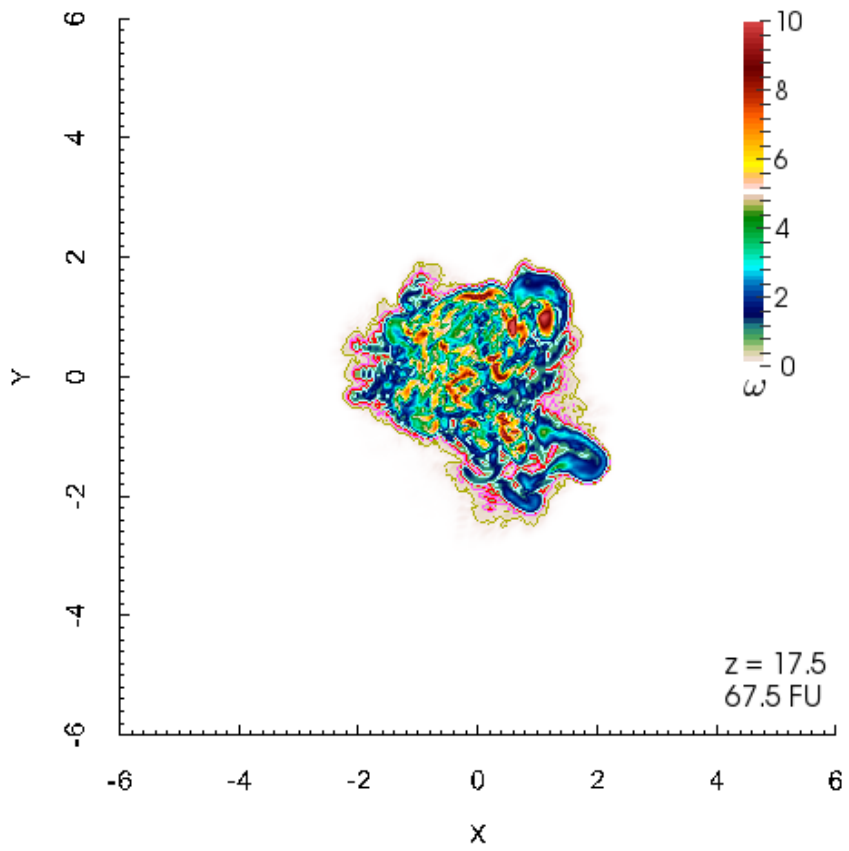
0
2
4
6
x
10
8
6
4
2
0
ω
HIZ
87.5 FU

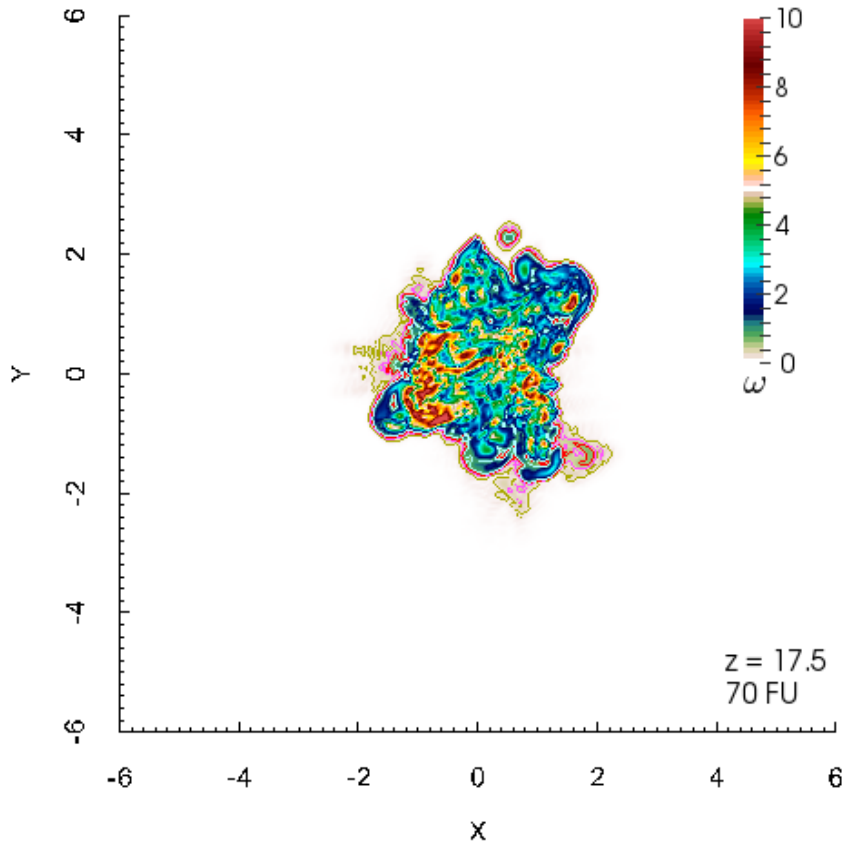

35
30
25
20
15
10
5
z
-6
-4
-2
0
2
4
6
x
10
8
6
4
2
0
ω
HIZ
90 FU

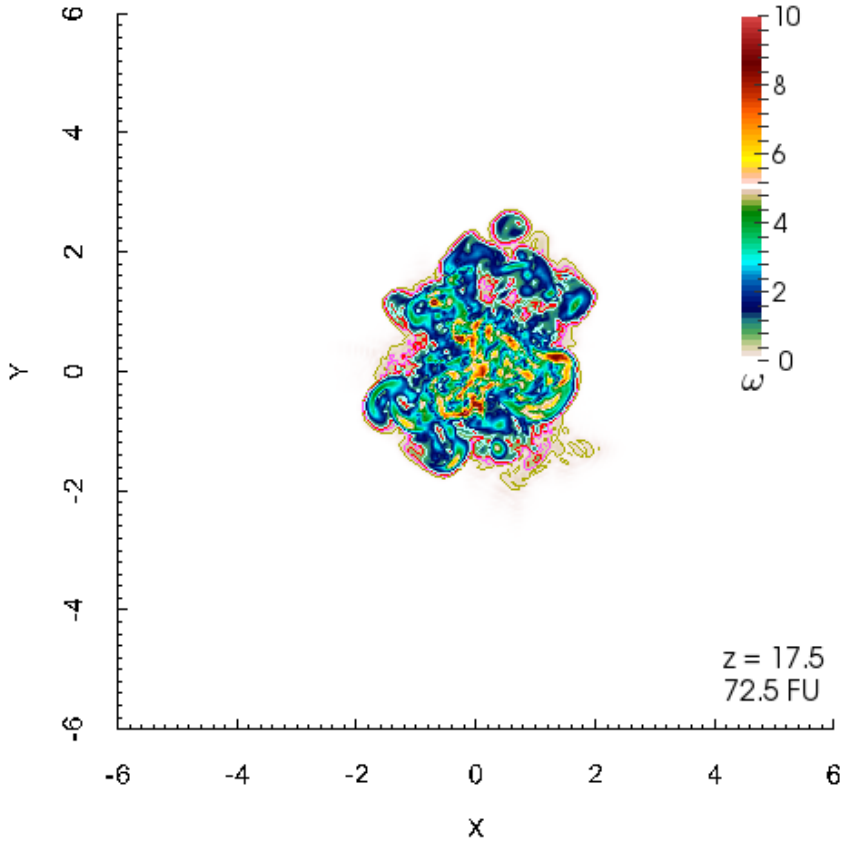
Diametral cross-sections

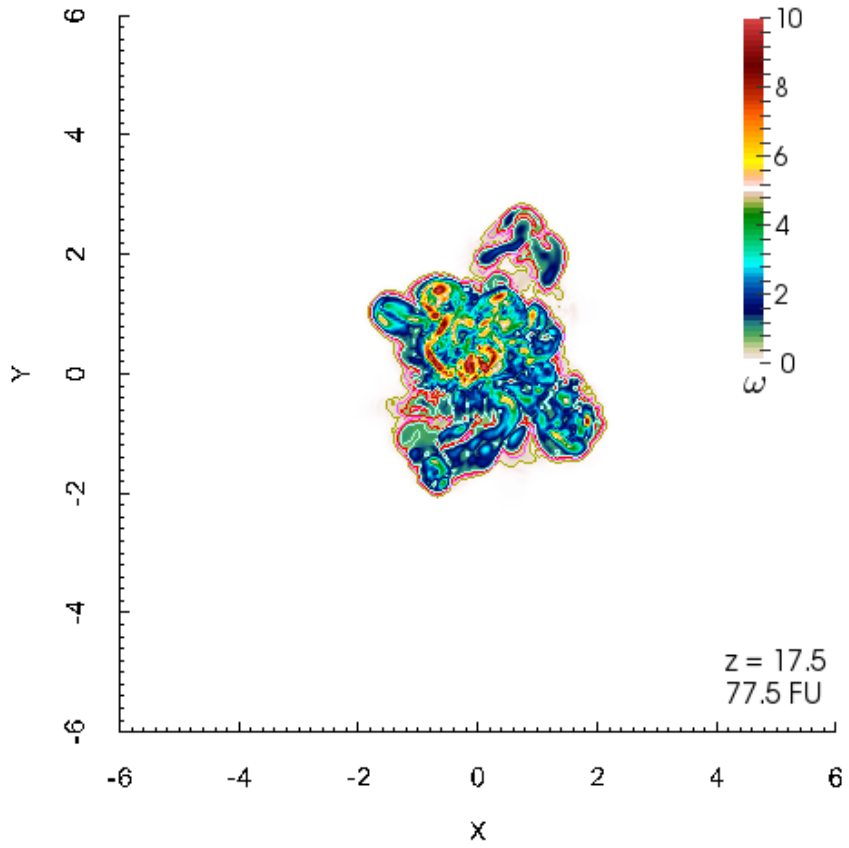
at z = 17.5, with time


10
8
6
4
2
0
ω
z = 17.5
65 FU
Y
X
-6
-4
-2
0
2
4
6


z = 17.5
67.5 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6


z = 17.5
70 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6


z = 17.5
72.5 FU
ω
10
8
6
4
2
0
Y
X
-6
-4
-2
0
2
4
6


z = 17.5
77.5 FU
X
Y
ω
10
8
6
4
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-6
-4
-2
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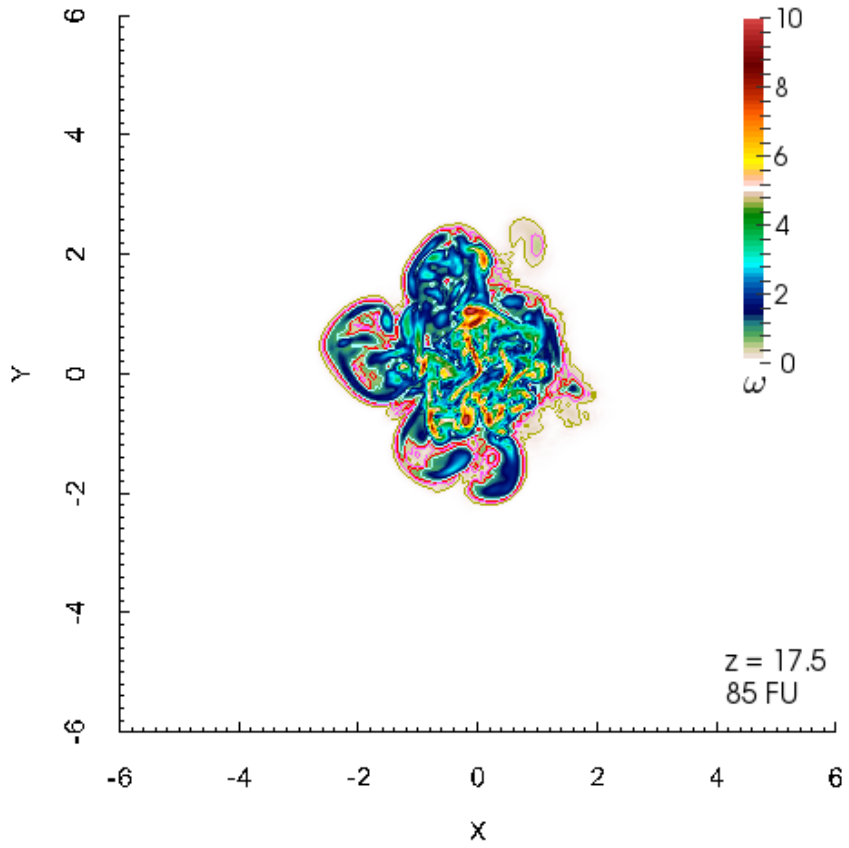
4
6


z = 17.5
85 FU
ω
10
8
6
4
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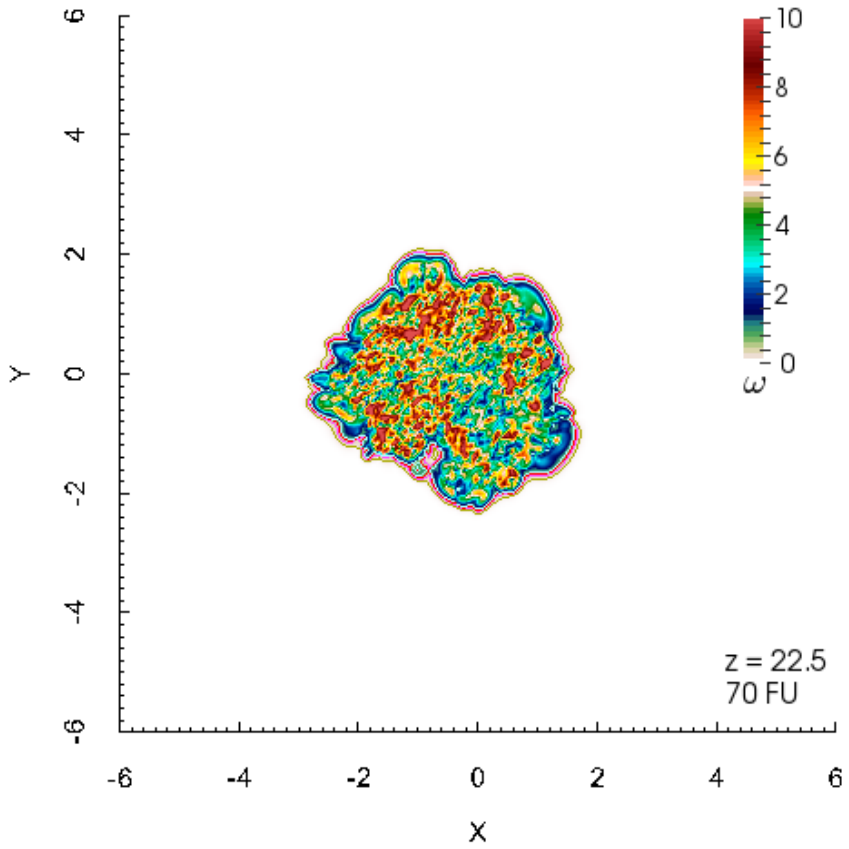
X
Y
-6
-4
-2
0
2
4
6

Diametral cross-sections

at z = 22.5, with time


z = 22.5
70 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
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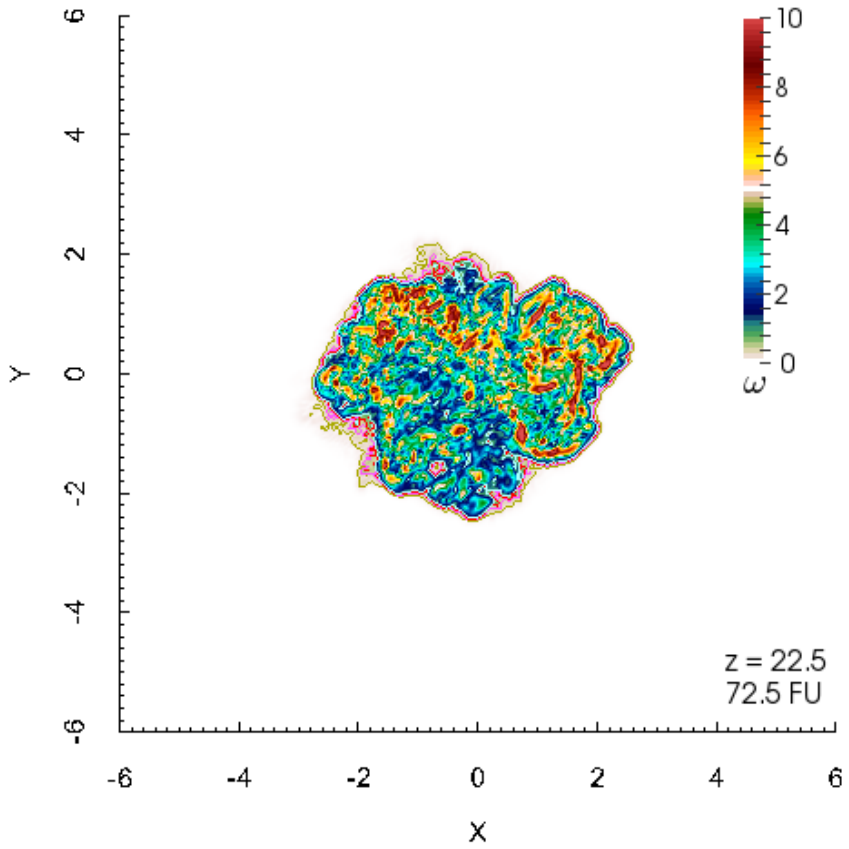
z = 22.5
72.5 FU
X
Y
ω
10
8
6
4
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-6
-4
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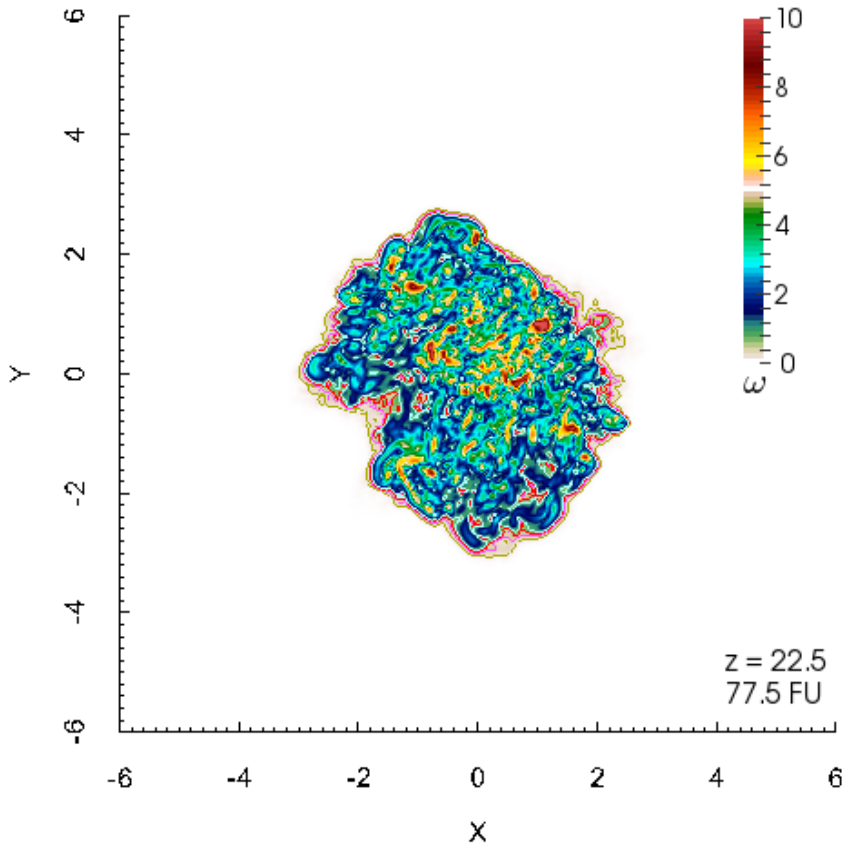
0
2
4
6


z = 22.5
77.5 FU
X
Y
ω
10
8
6
4
2
0
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-4
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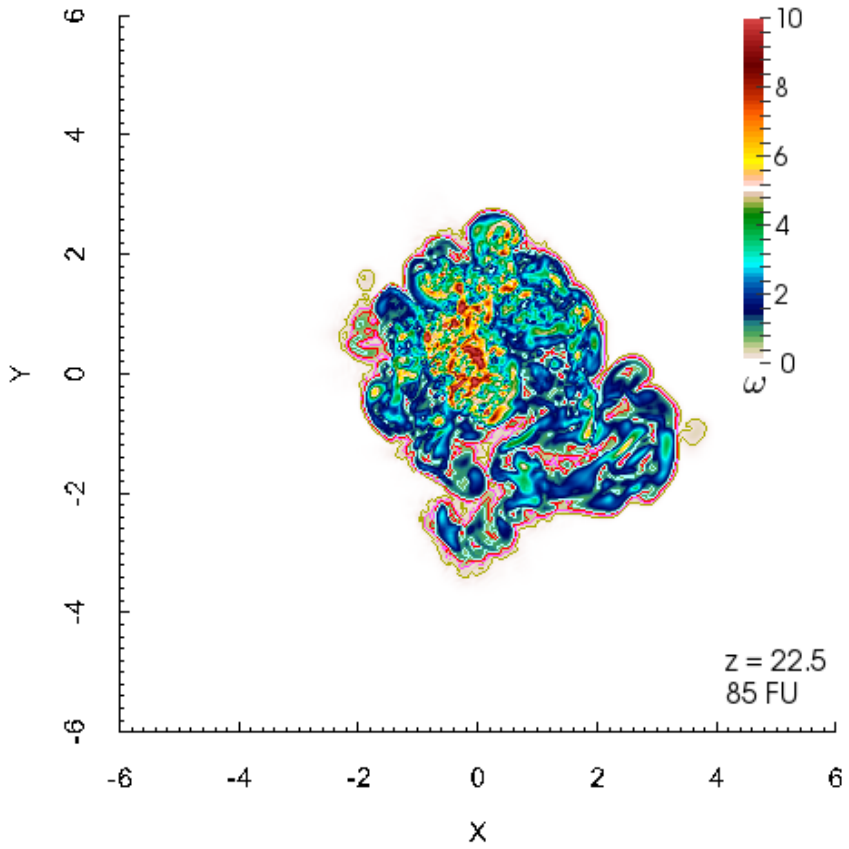
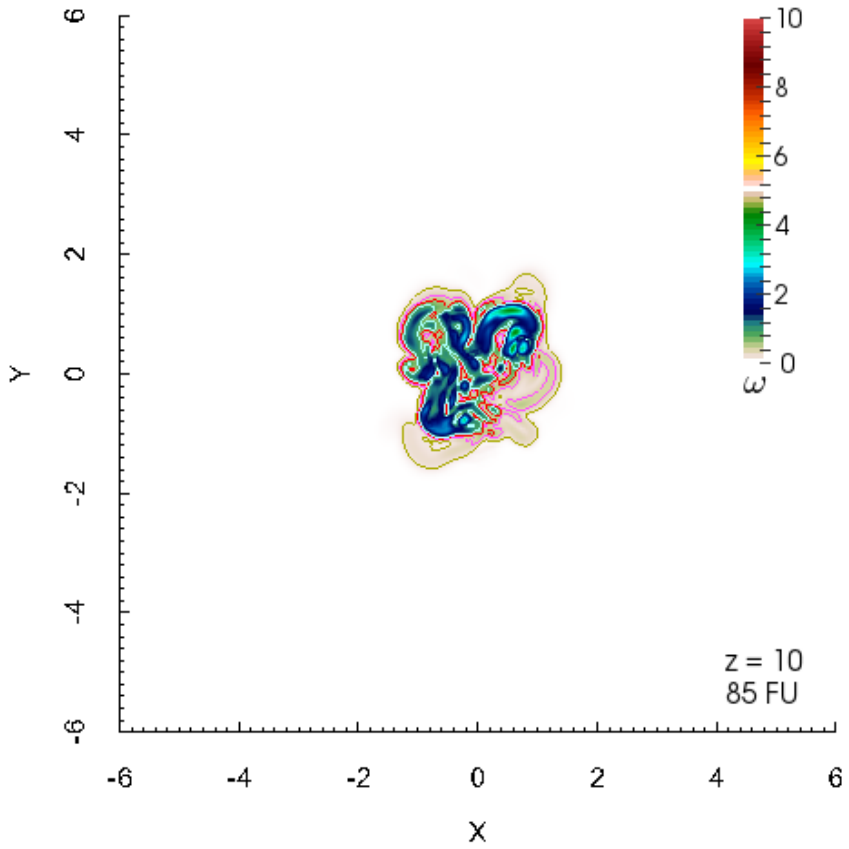
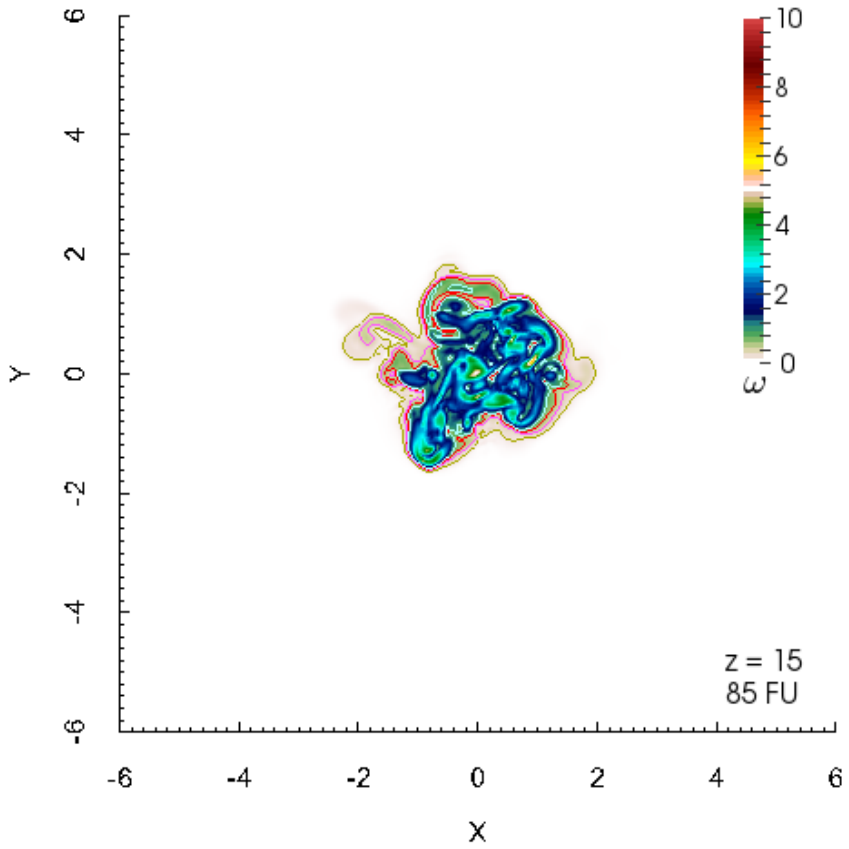
0
2
4
6


z = 22.5
85 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6

Diametral cross-sections

at 85 FU, with z


Y
X
ω
z = 10
85 FU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X
Y
ω
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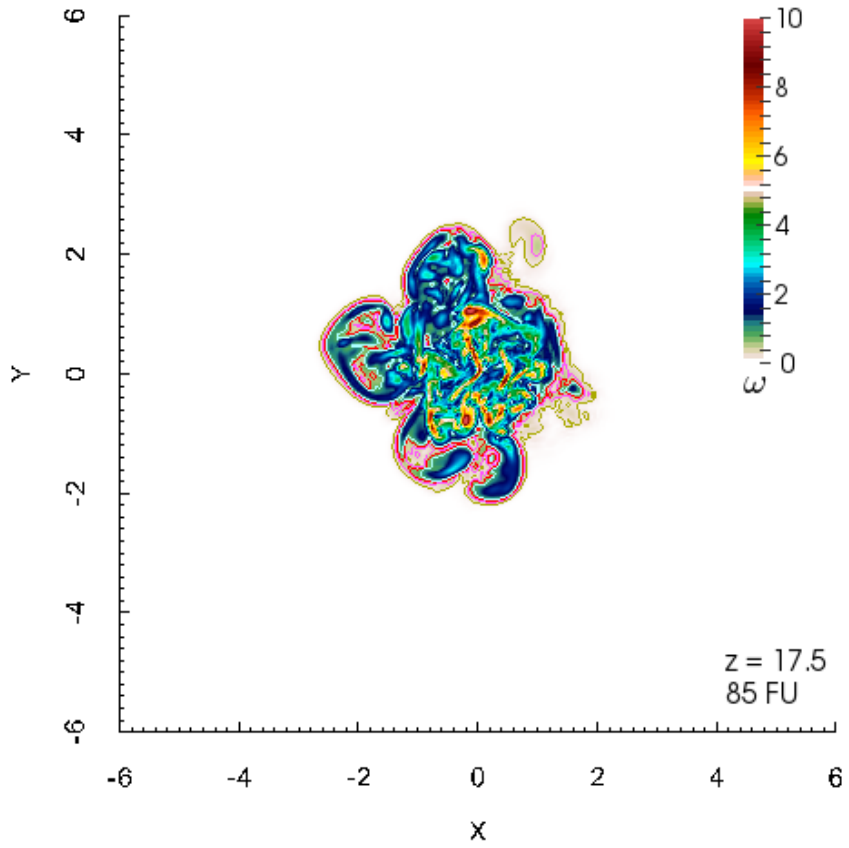
0
2
4
6


z = 17.5
85 FU
ω
10
8
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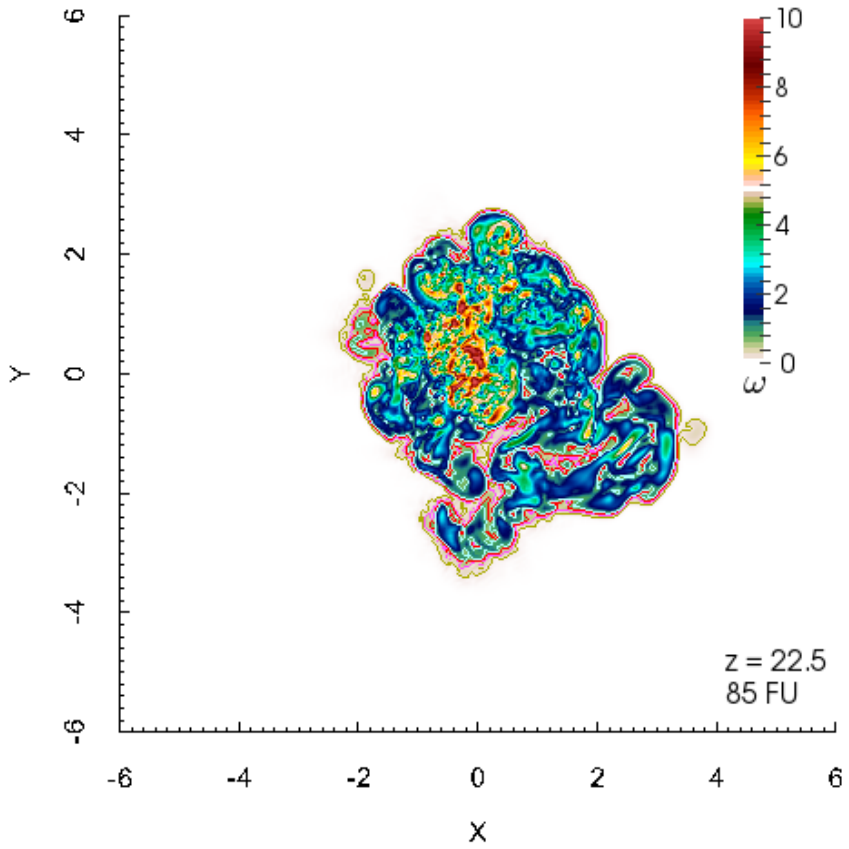
4
2
0
X
Y
-6
-4
-2
0
2
4
6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85 FU
X
Y
ω
10
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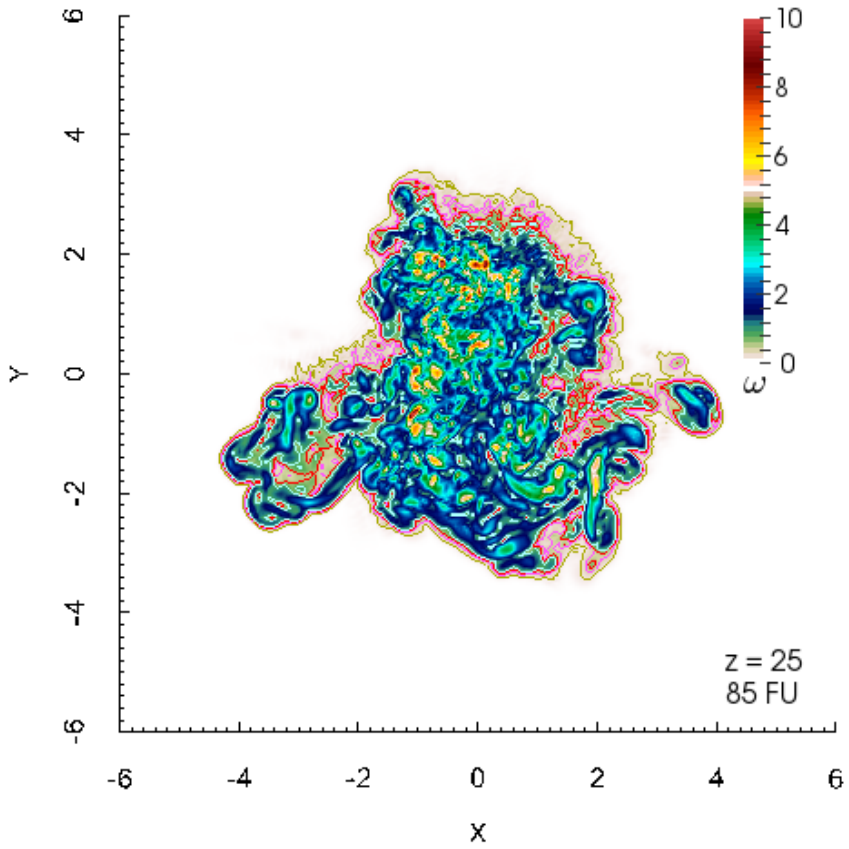
0
-6
-4
-2
0
2
4
6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X
Y
ω
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-2
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8
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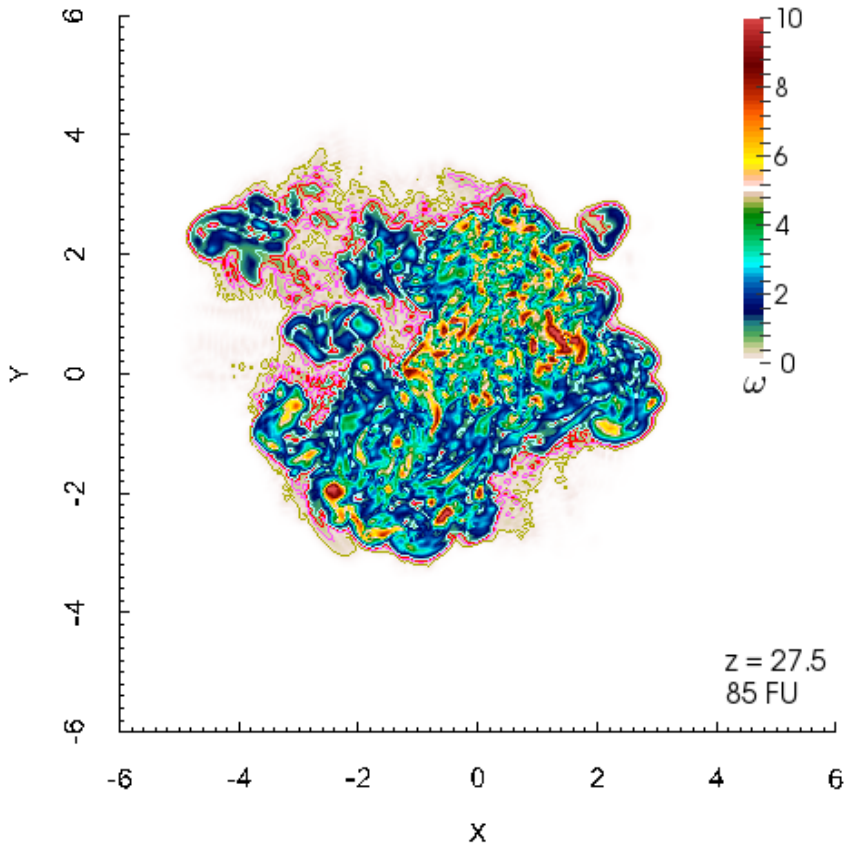
4
2
0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X
Y
ω
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-4
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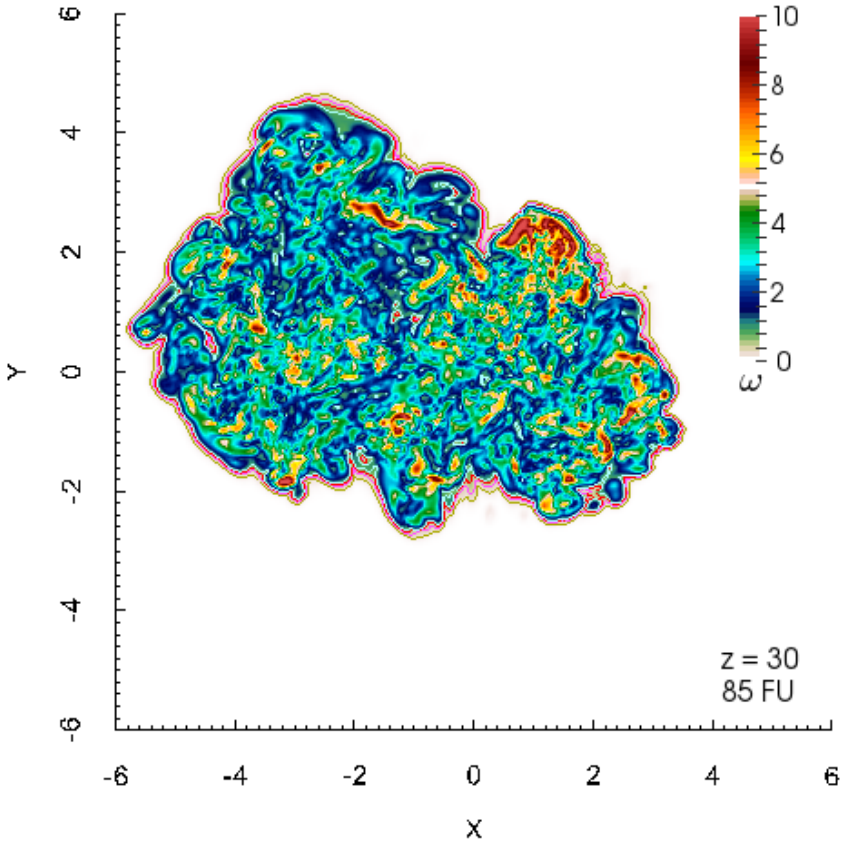
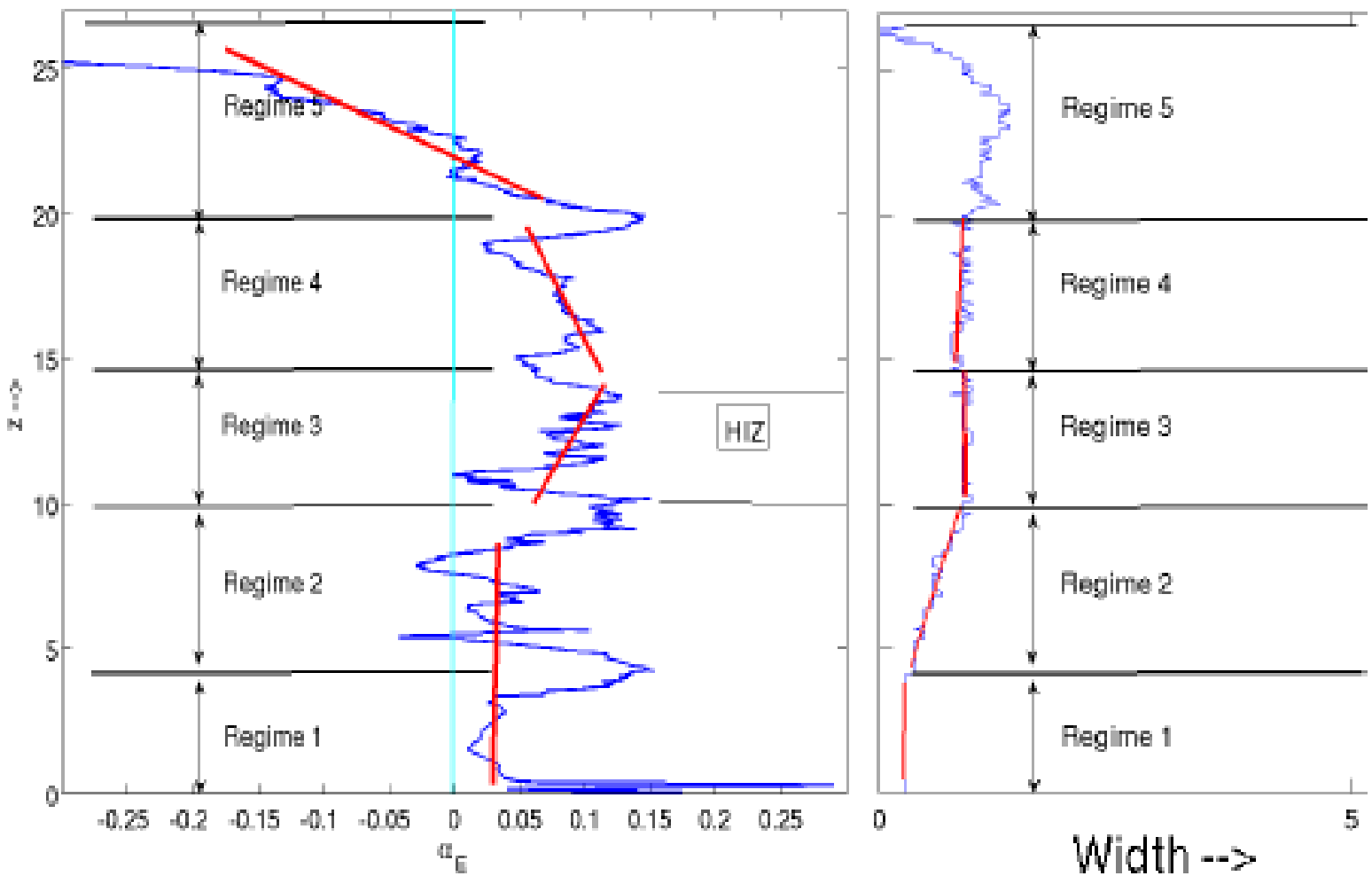
0
2
4
6


z = 30
85 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6

Entrainment coefficient and width



TRANSIENT DIABATIC PLUME

Re = 2000

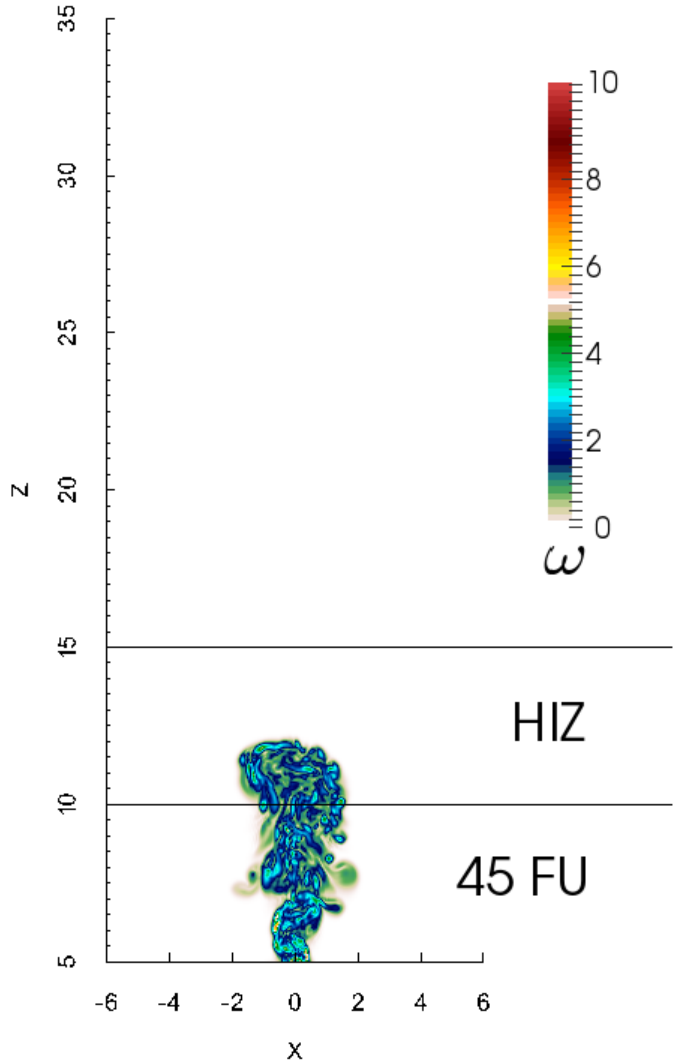
Totally 90 FU

HIZ : 10 – 15 diameters

Heating stops at 65 FU

HEATING PROFILE HISTORY

Axial sections at $y = 0$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30
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20
15
10
5
z
-6
-4
-2
0
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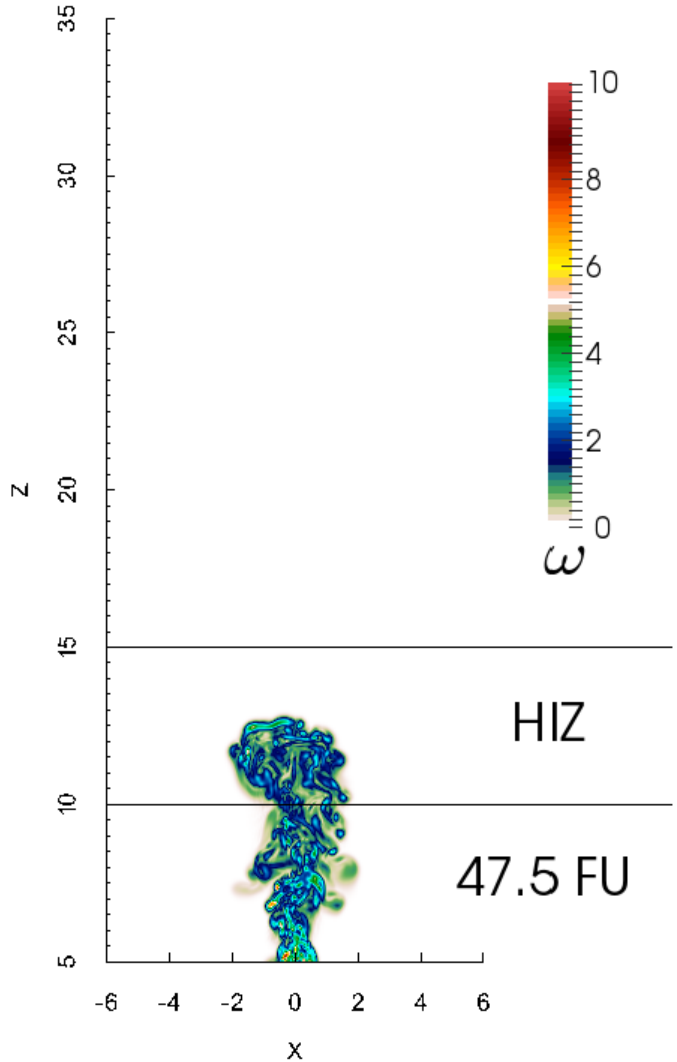
4
6
x
10
8
6
4
2
0
ω
HIZ
45 FU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30
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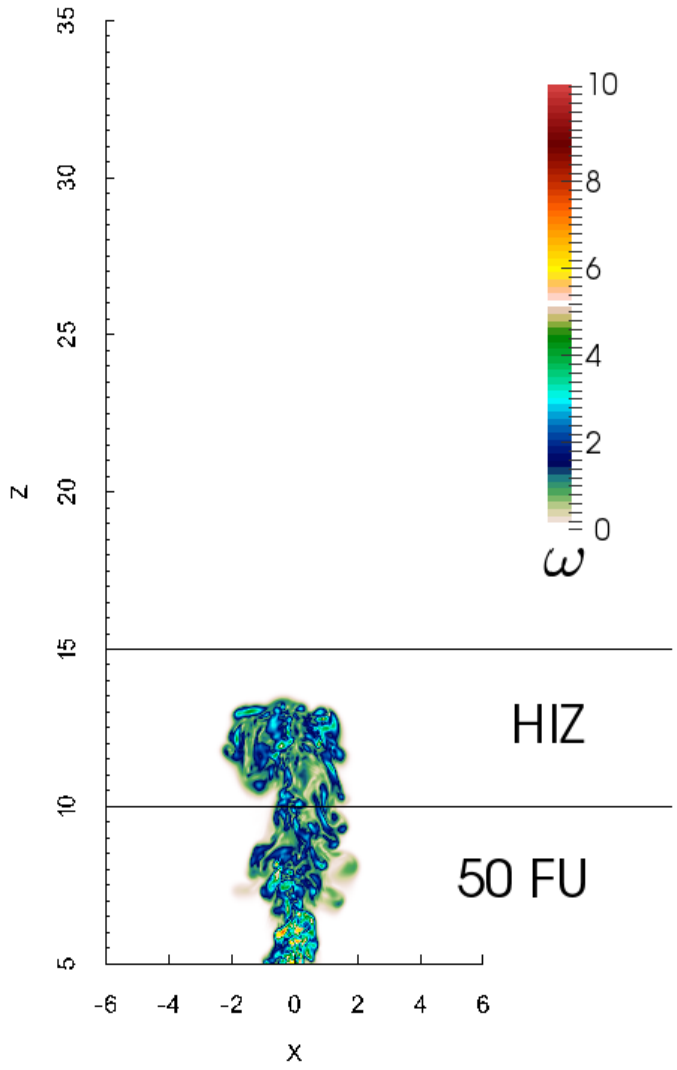
20
15
10
5
z
-6
-4
-2
0
2
4
6
x
10
8
6
4
2
0
ω
HIZ
47.5 FU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0
ω
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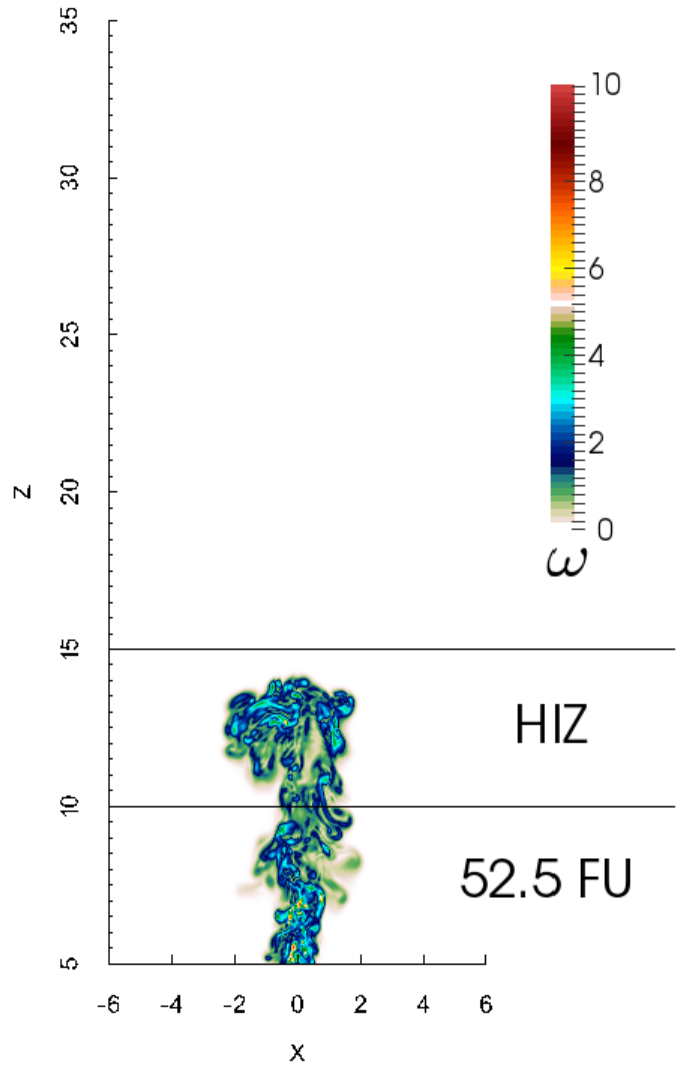
50 FU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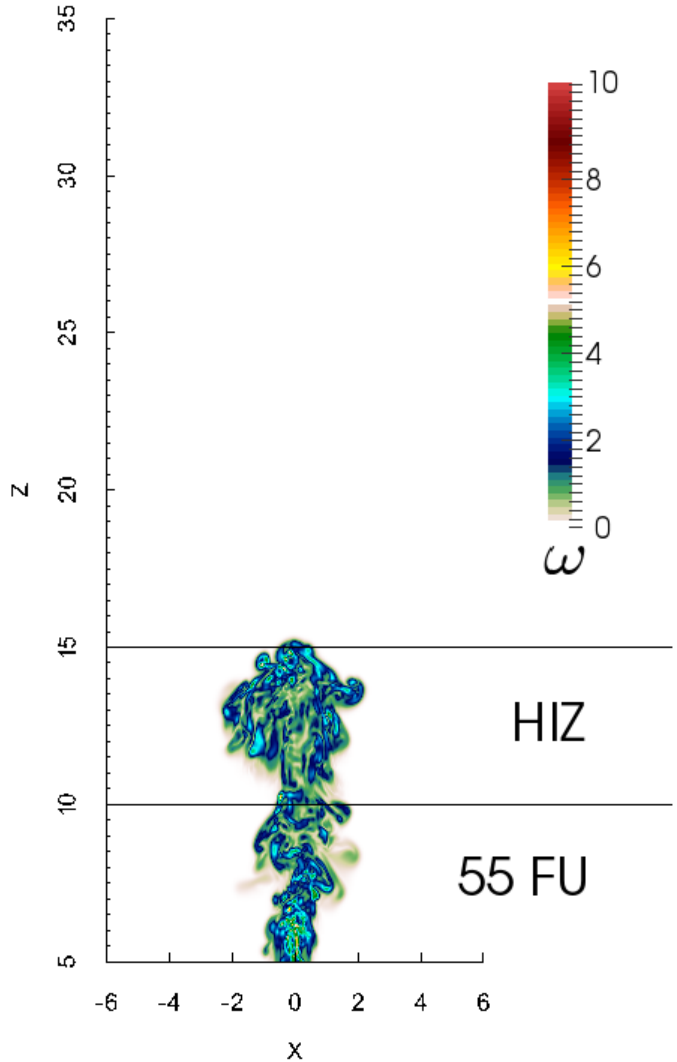
52.5 FU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0
ω
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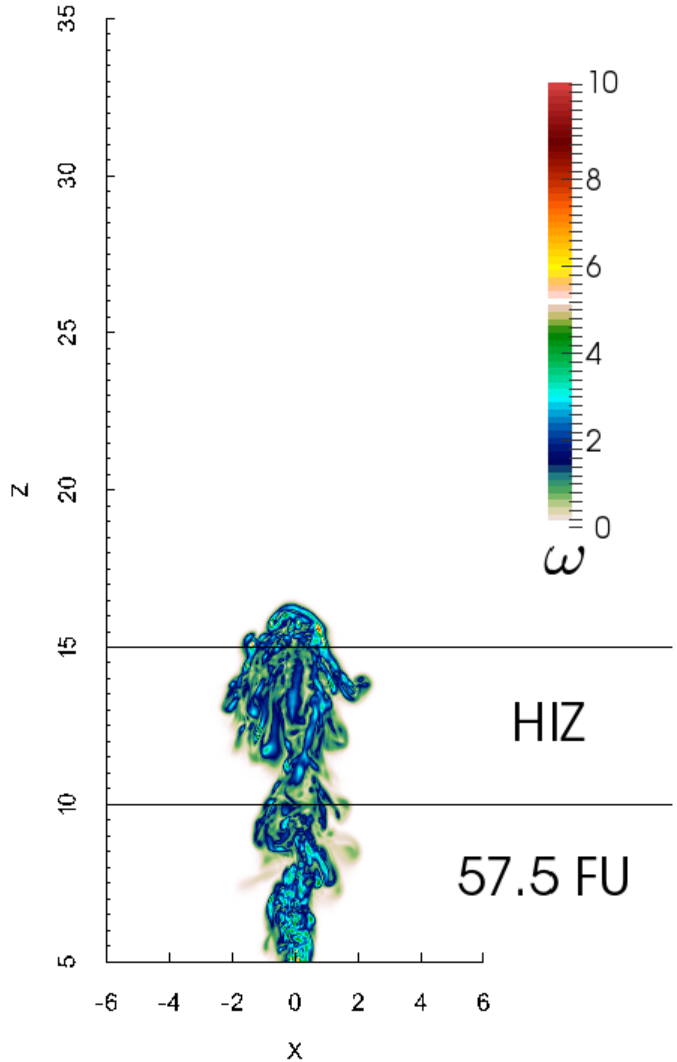
55 FU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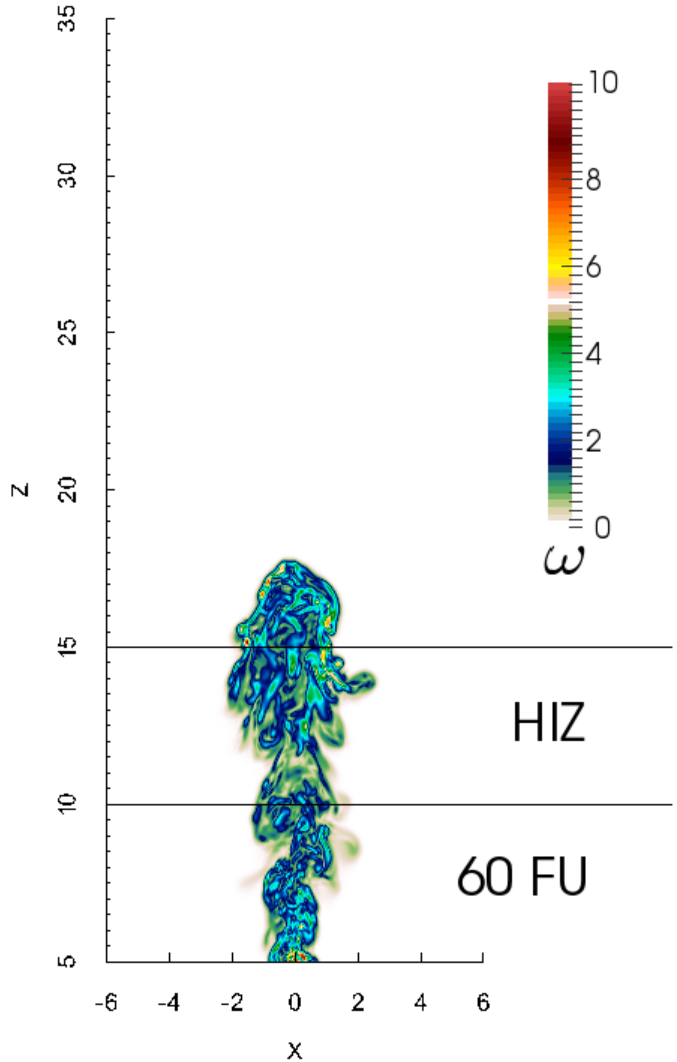
57.5 FU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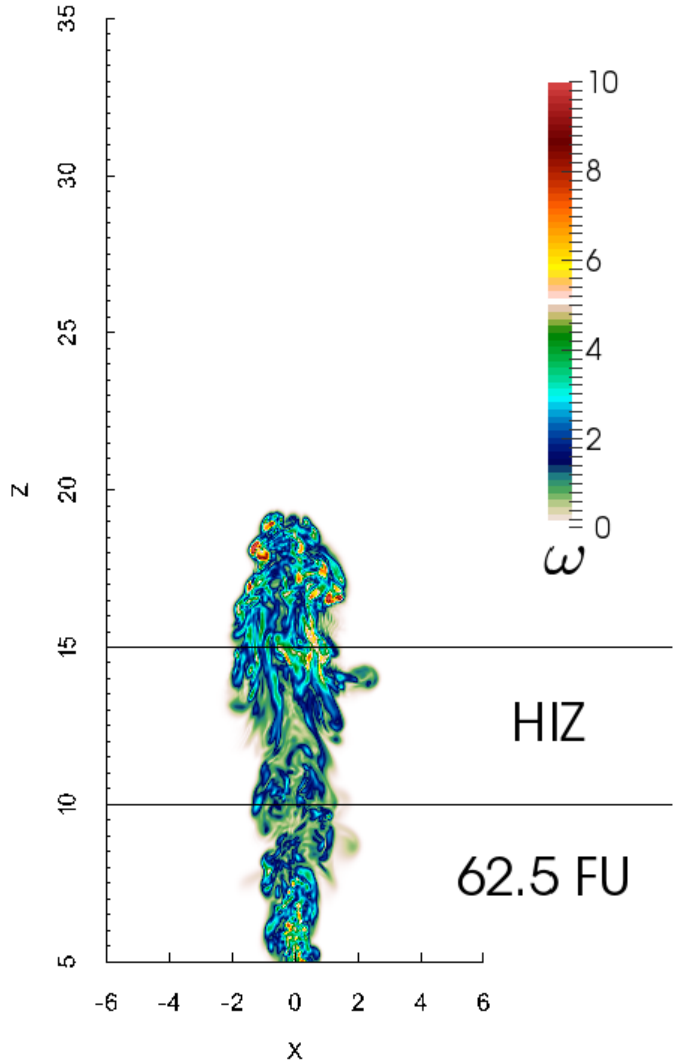
0
ω
HIZ
60 FU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4
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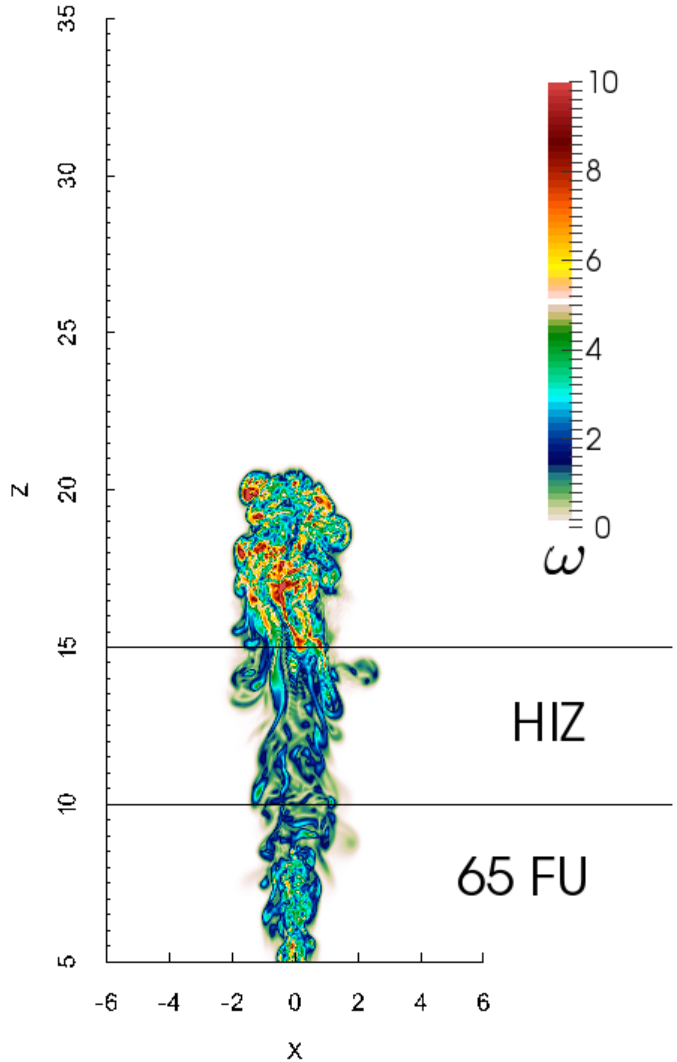
0
ω
HIZ
62.5 FU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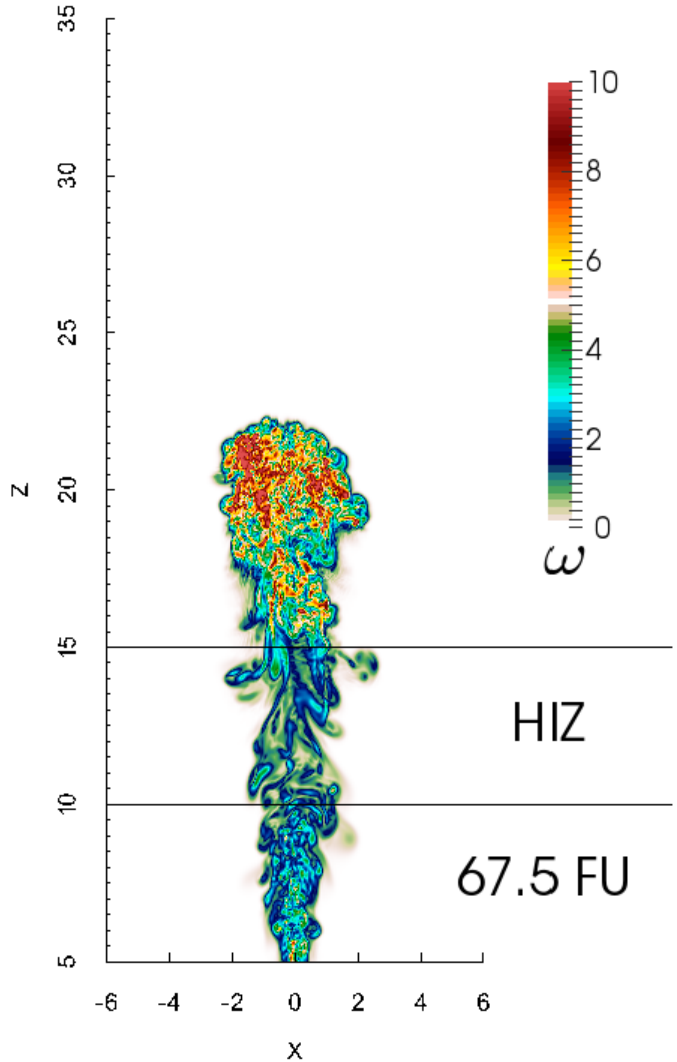
0
ω
HIZ
65 FU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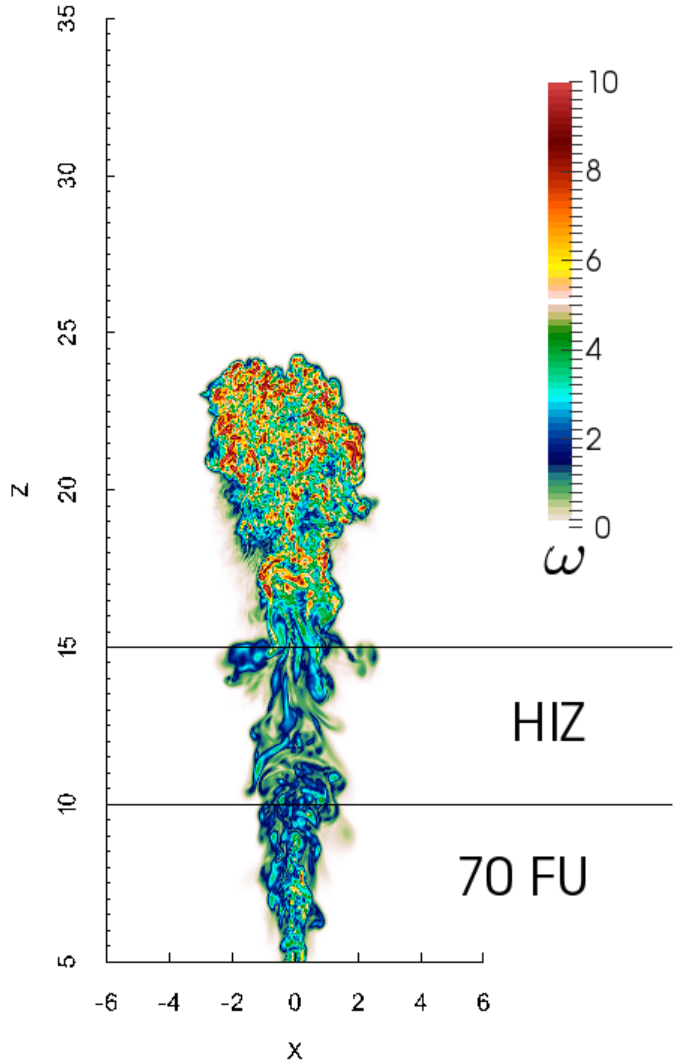
0
ω
HIZ
67.5 FU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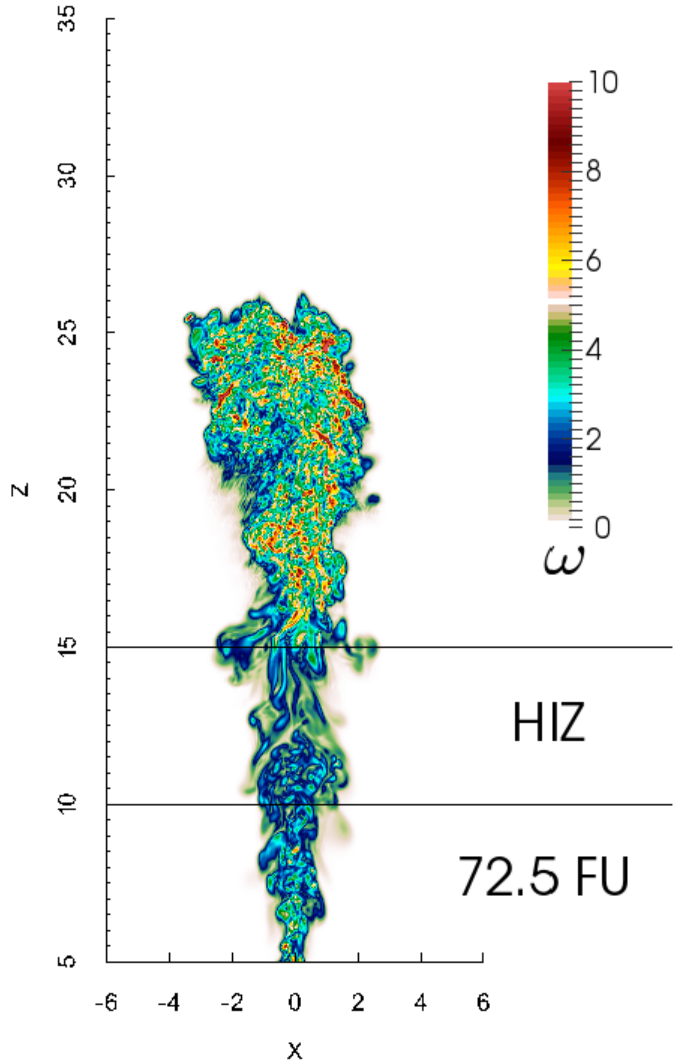
0
ω
HIZ
70 FU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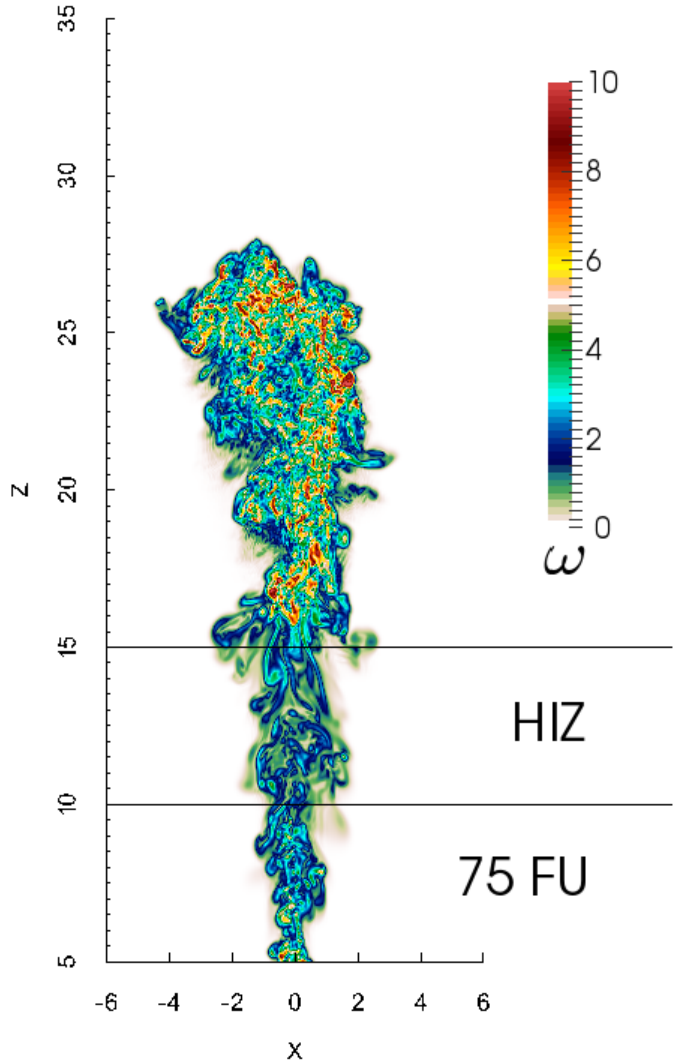
0
ω
HIZ
72.5 FU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4
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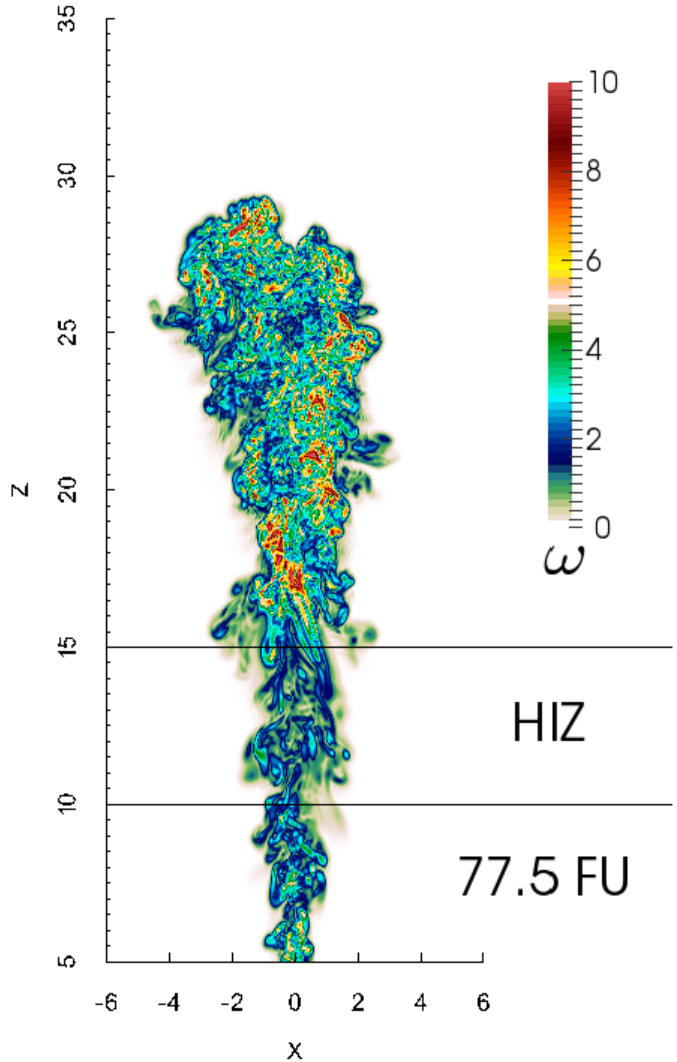
0
ω
HIZ
75 FU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4
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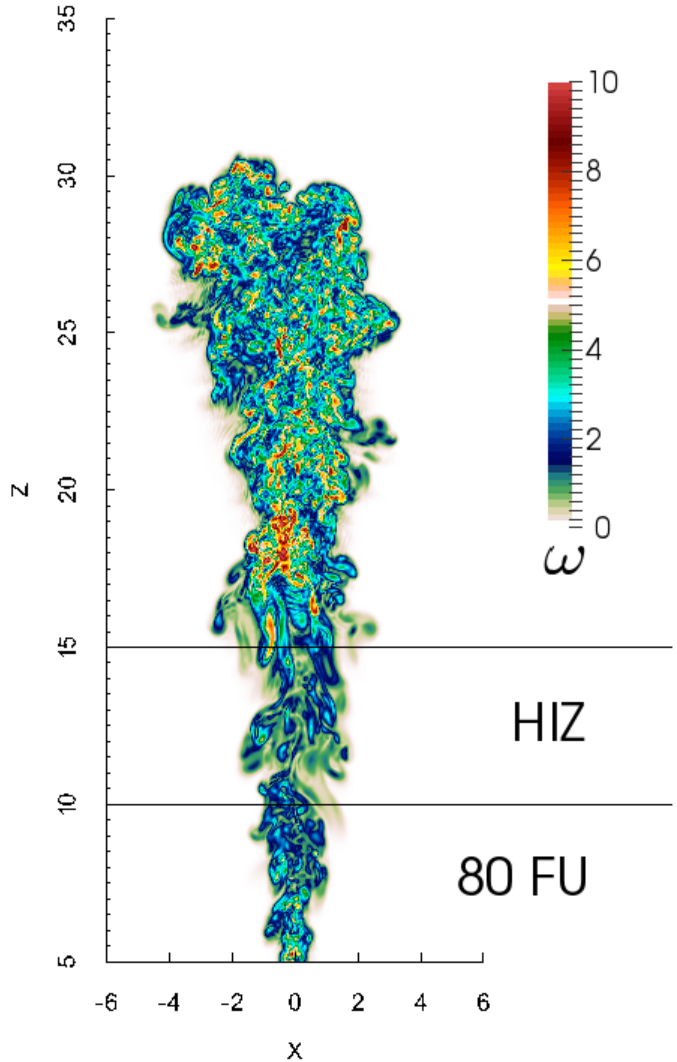
0
ω
HIZ
77.5 FU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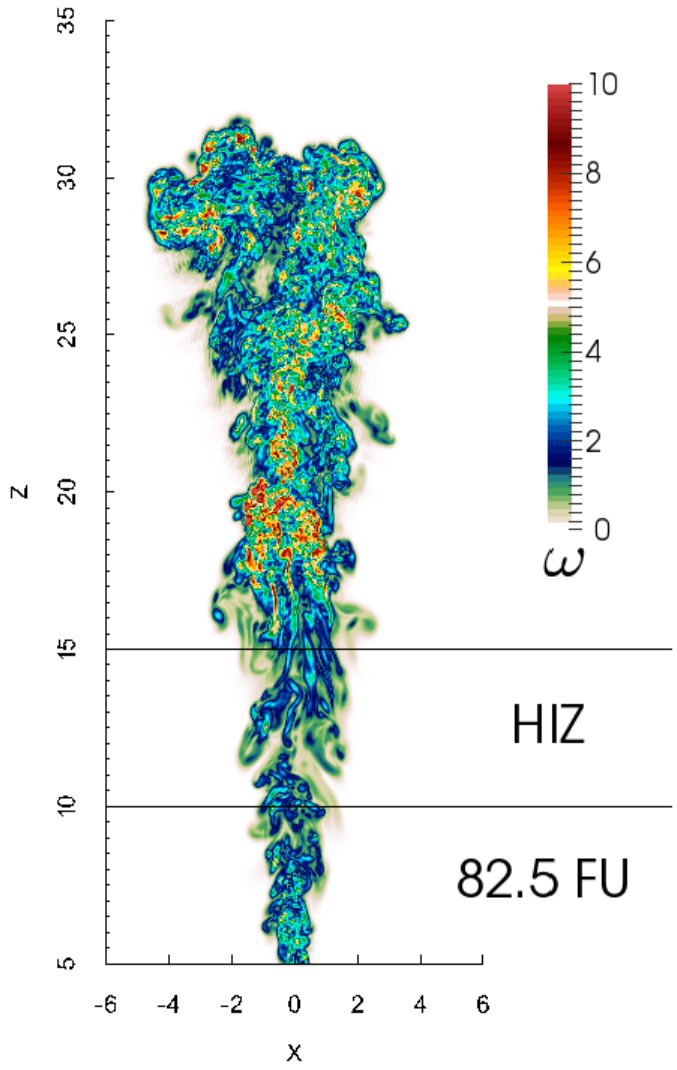
0
ω
HIZ
80 FU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x
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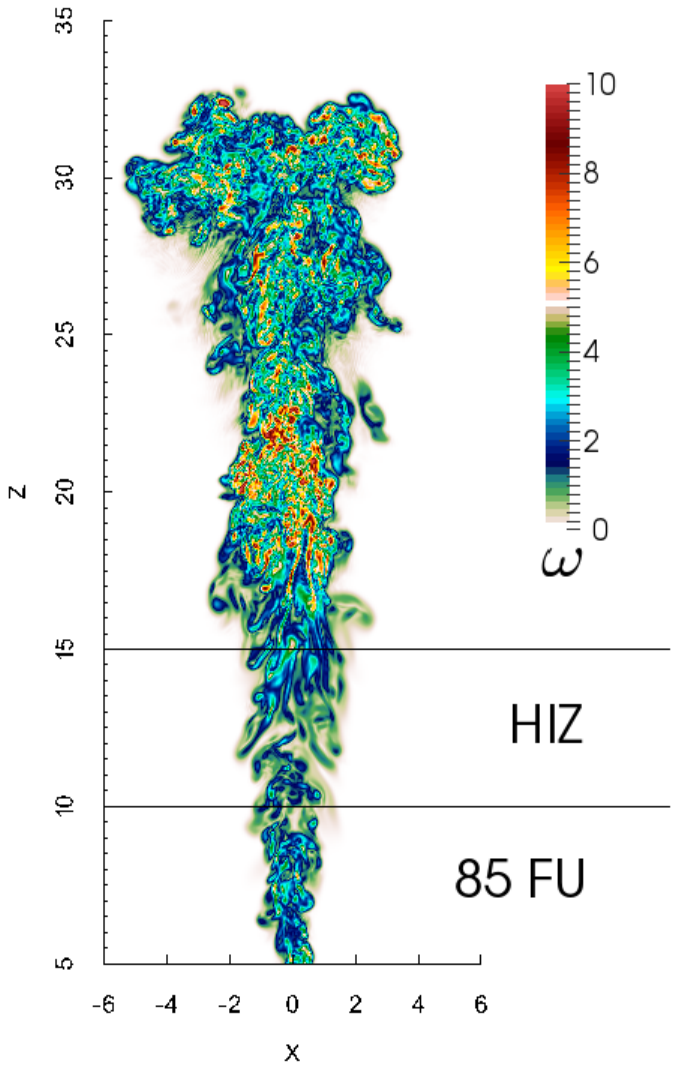
4
2
0
ω
HIZ
82.5 FU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4
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x
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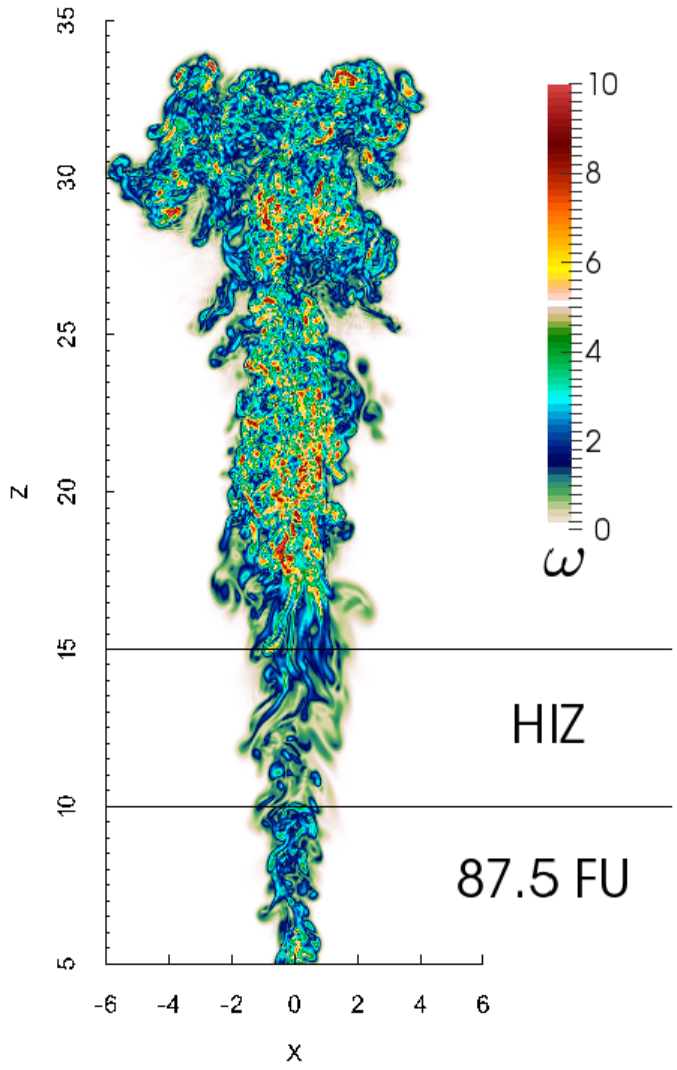
8
6
4
2
0
ω
HIZ
85 FU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x
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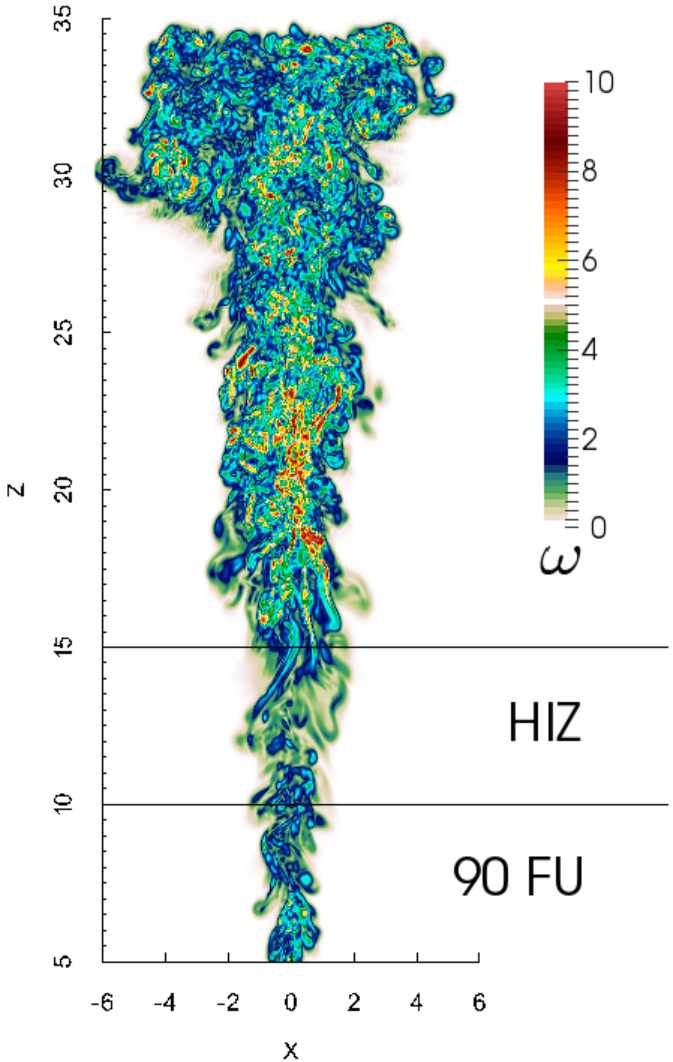
4
2
0
ω
HIZ
87.5 FU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30
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15
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z
-6
-4
-2
0
2
4
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x
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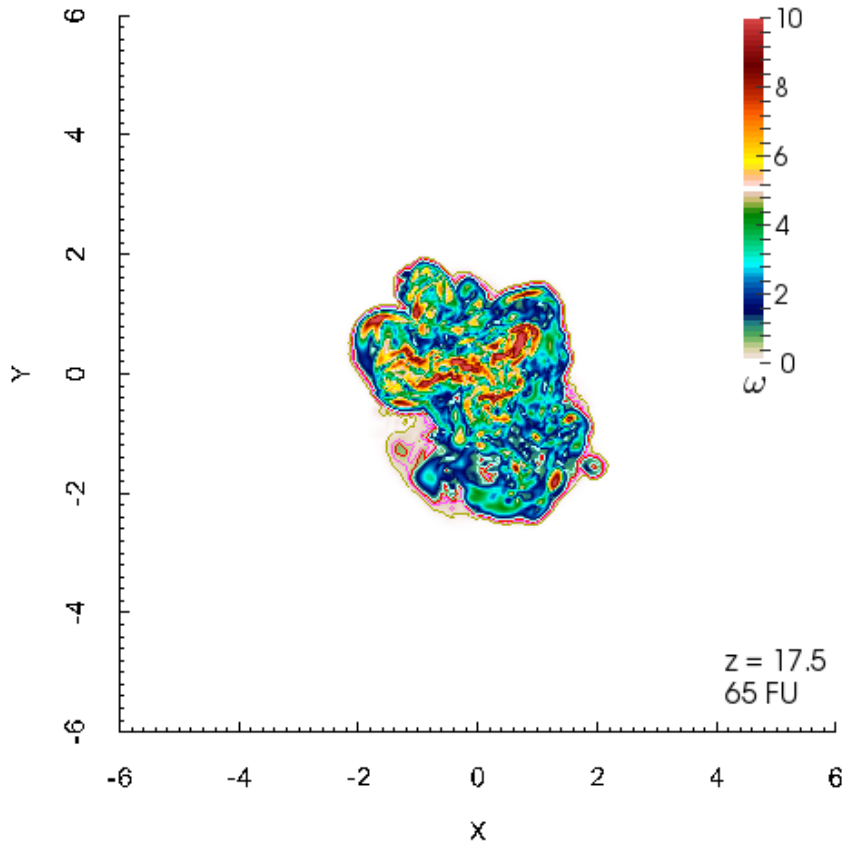
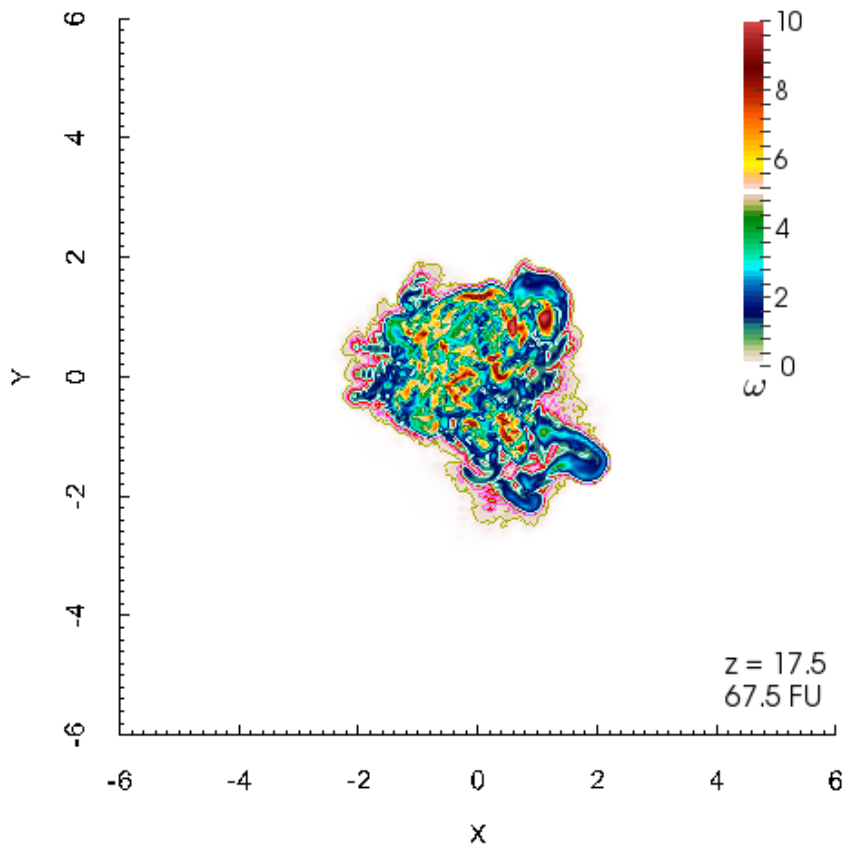
8
6
4
2
0
ω
HIZ
90 FU

Diametral cross-sections

at z = 17.5, with time


10
8
6
4
2
0
ω
z = 17.5
65 FU
Y
X
-6
-4
-2
0
2
4
6


z = 17.5
67.5 FU
X
Y
ω
10
8
6
4
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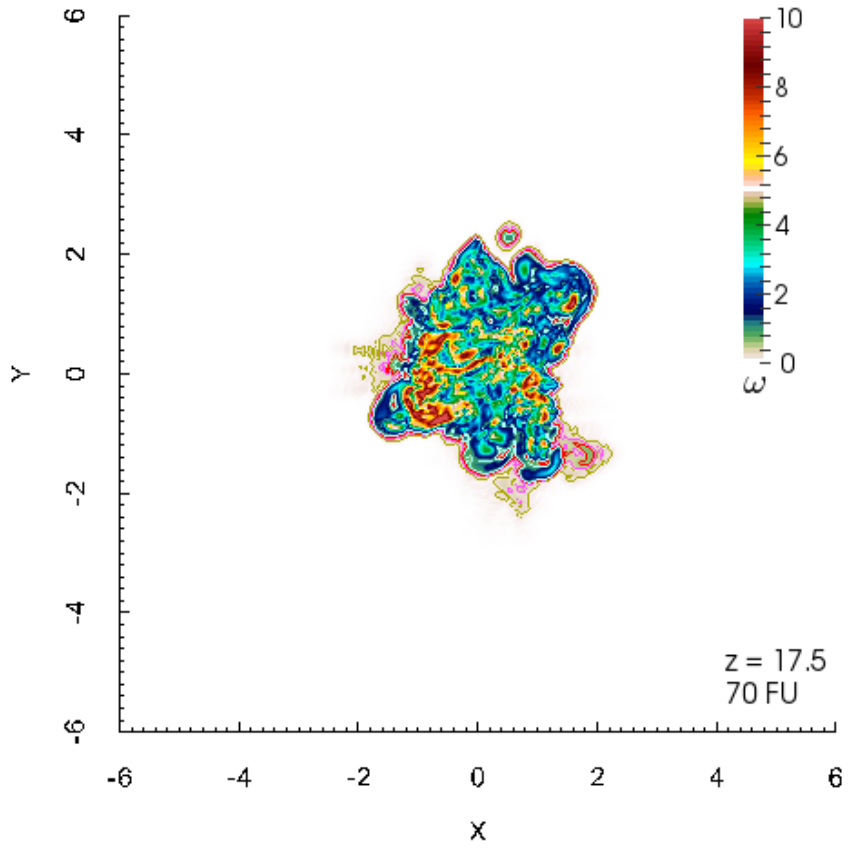
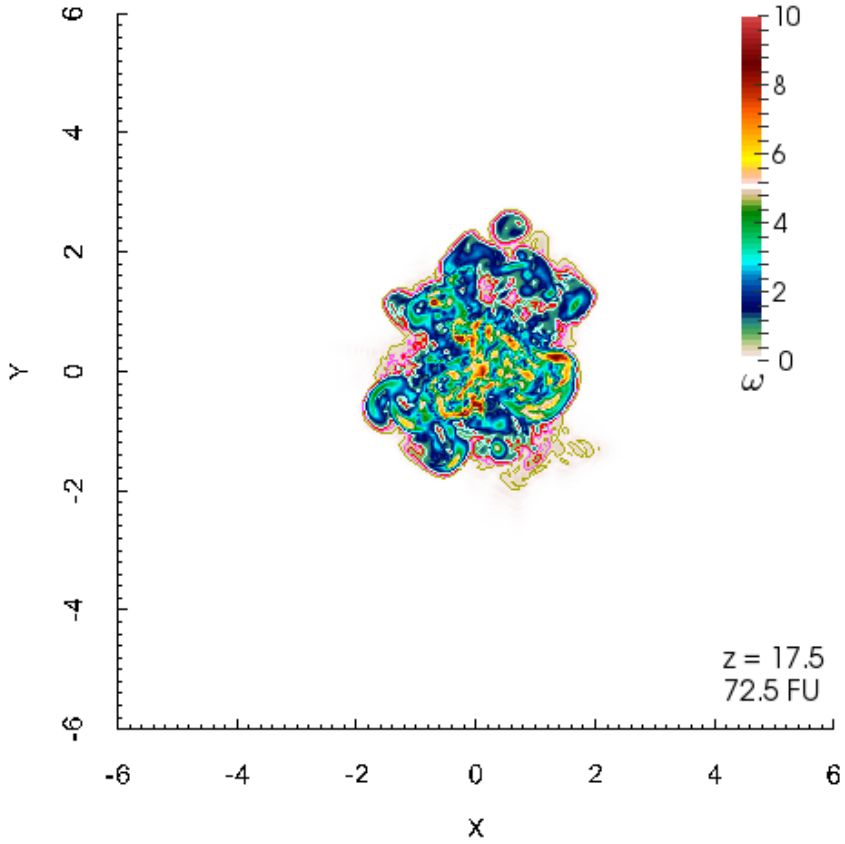
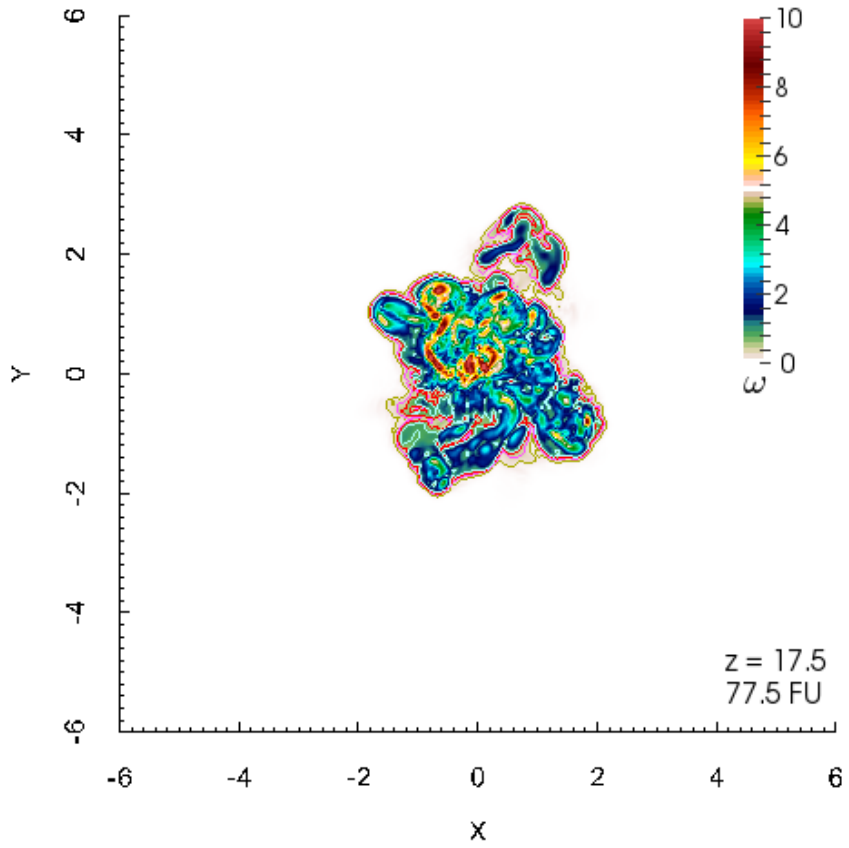
0
-6
-4
-2
0
2
4
6


z = 17.5
70 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6


z = 17.5
72.5 FU
ω
10
8
6
4
2
0
Y
X
-6
-4
-2
0
2
4
6


z = 17.5
77.5 FU
X
Y
ω
10
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6
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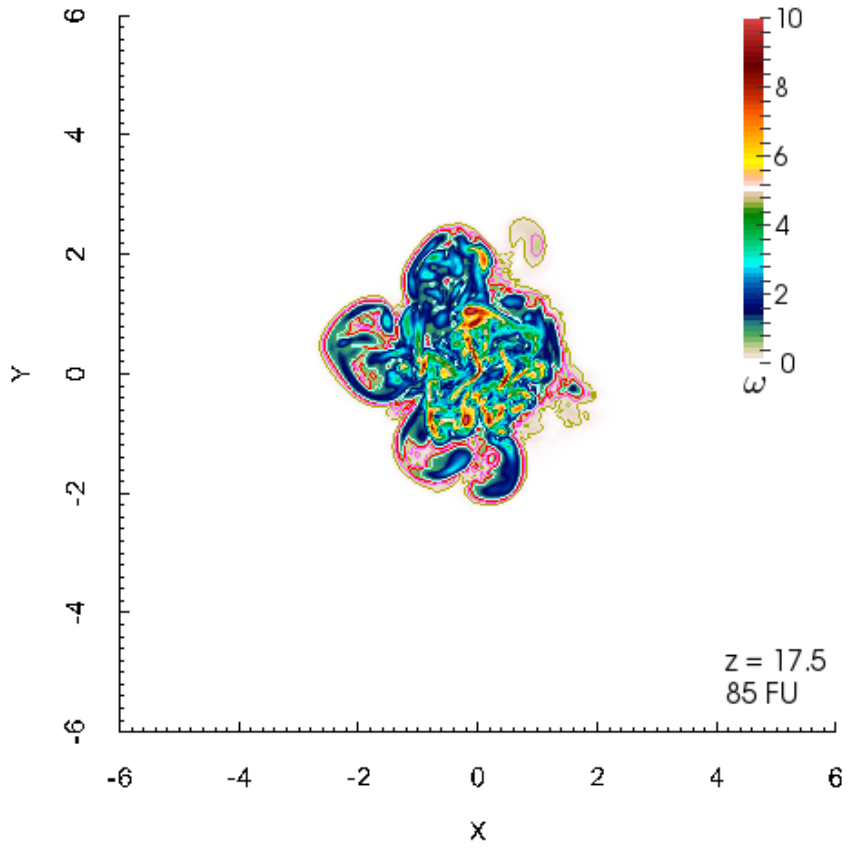
2
0
-6
-4
-2
0
2
4
6


z = 17.5
85 FU
ω
10
8
6
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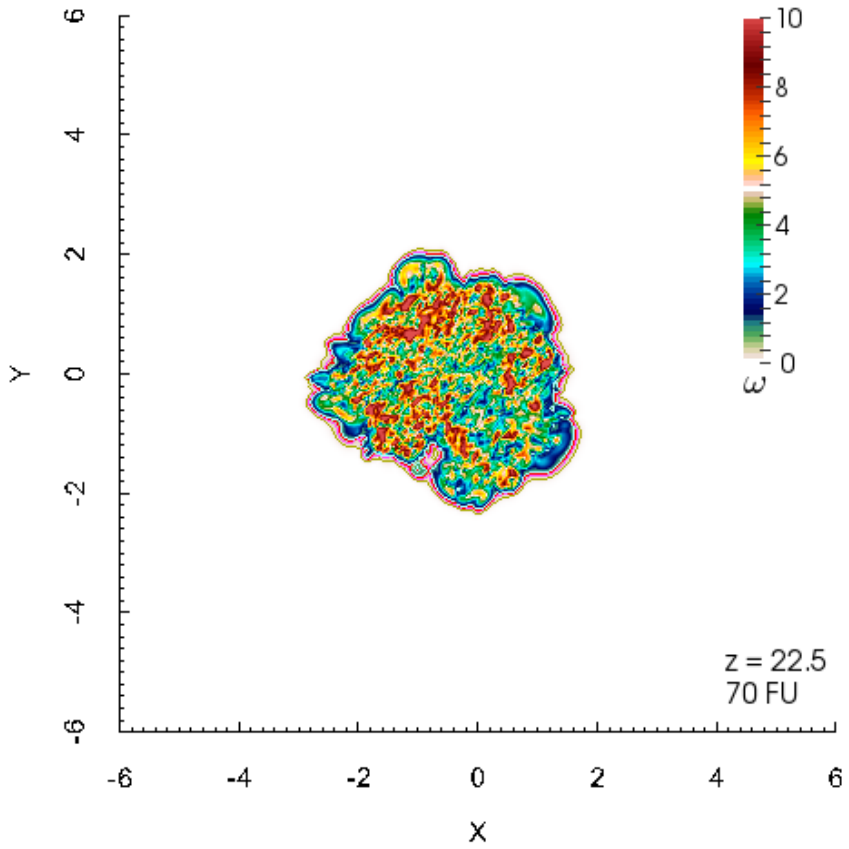
X
Y
-6
-4
-2
0
2
4
6

Diametral cross-sections

at z = 22.5, with time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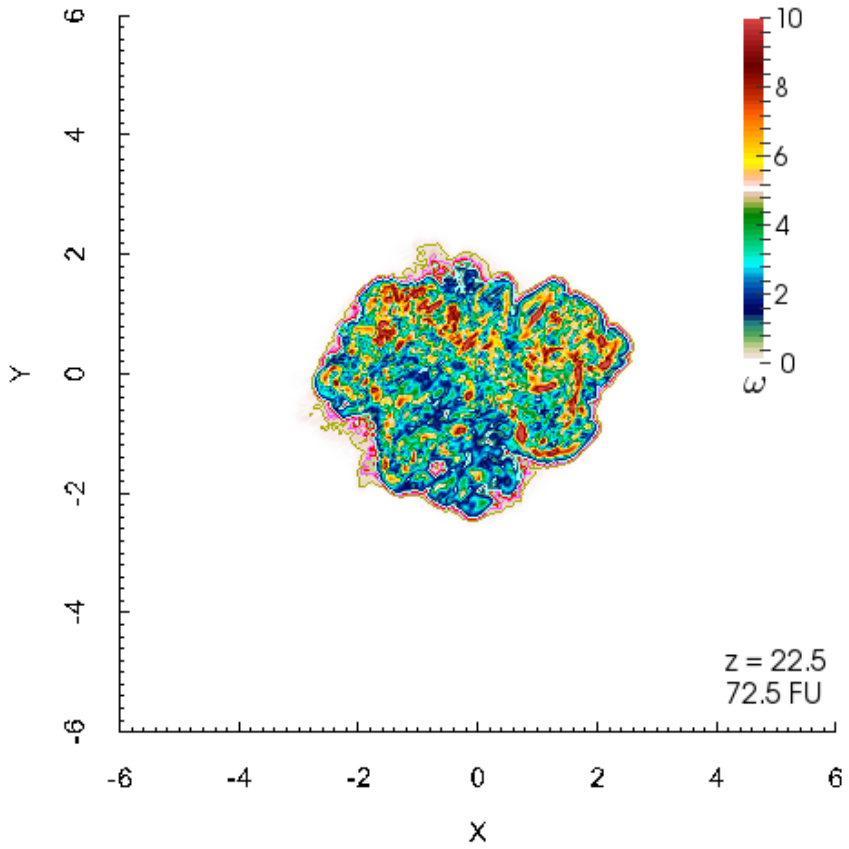
70 FU
X
Y
ω
10
8
6
4
2
0
-6
-4
-2
0
2
4
6


z = 22.5
72.5 FU
X
Y
ω
10
8
6
4
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-6
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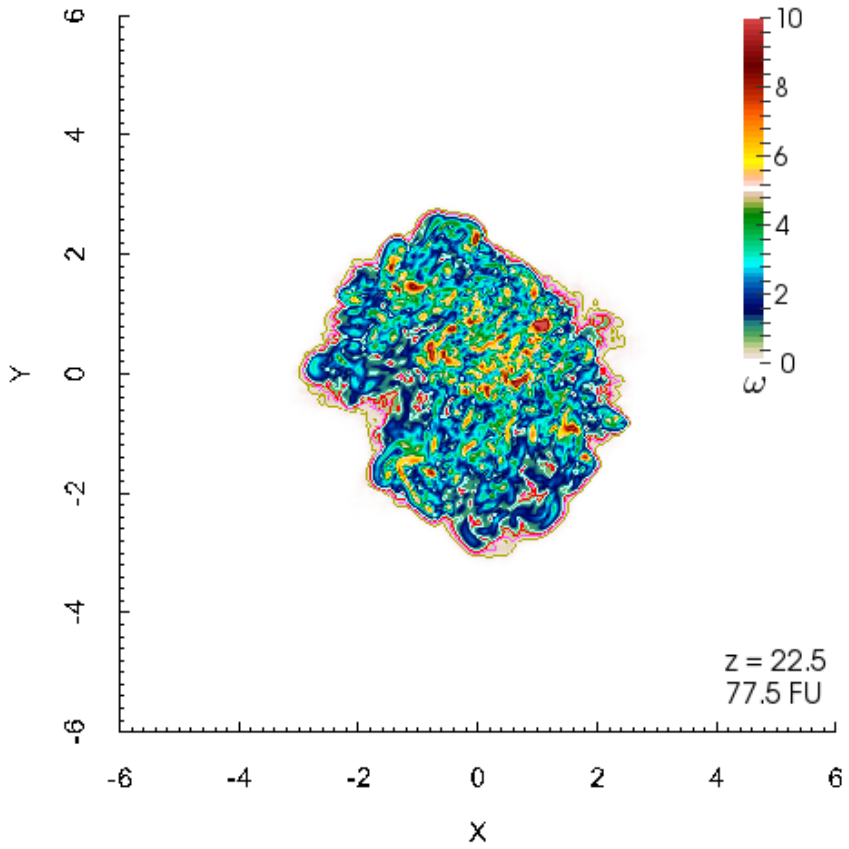
0
2
4
6


z = 22.5
77.5 FU
X
Y
ω
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4
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-4
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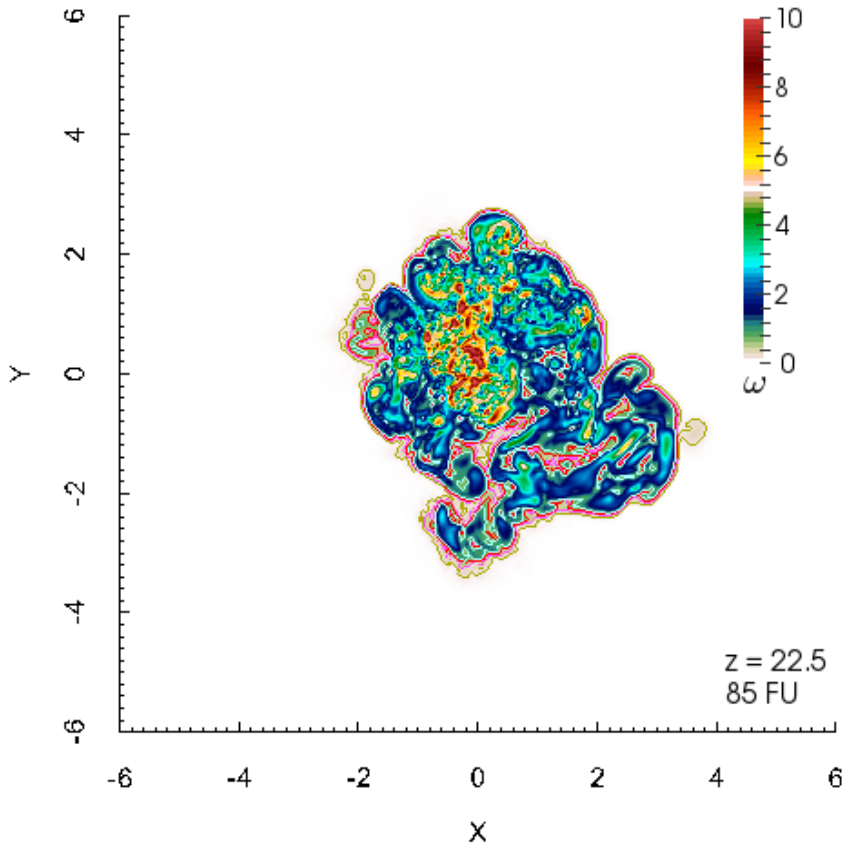
4
6


z = 22.5
85 FU
X
Y
ω
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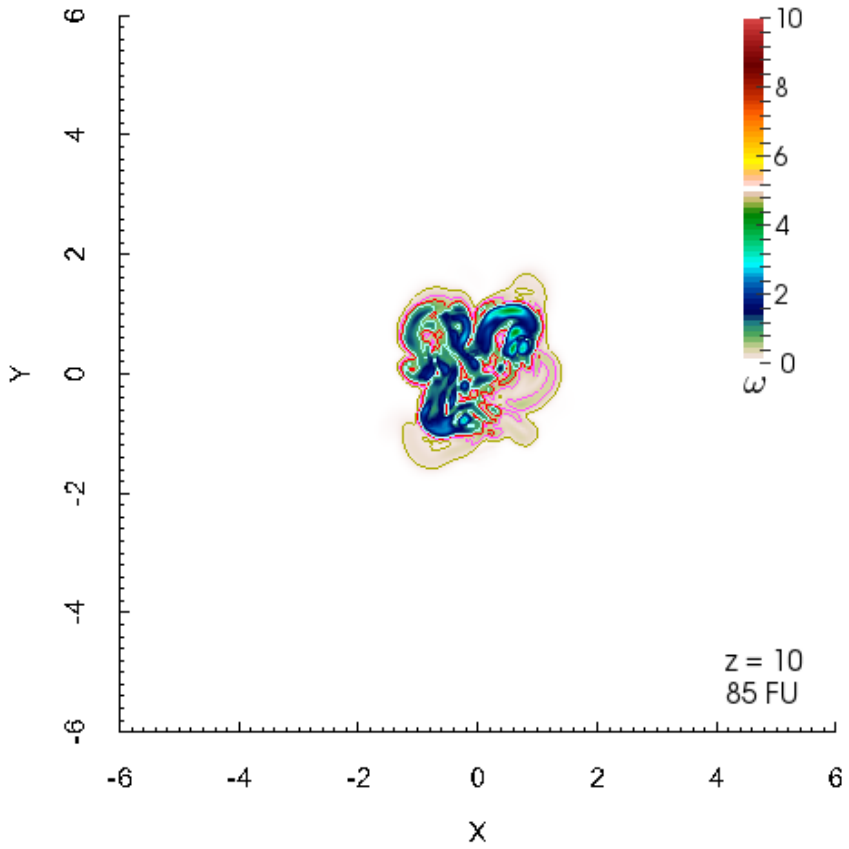
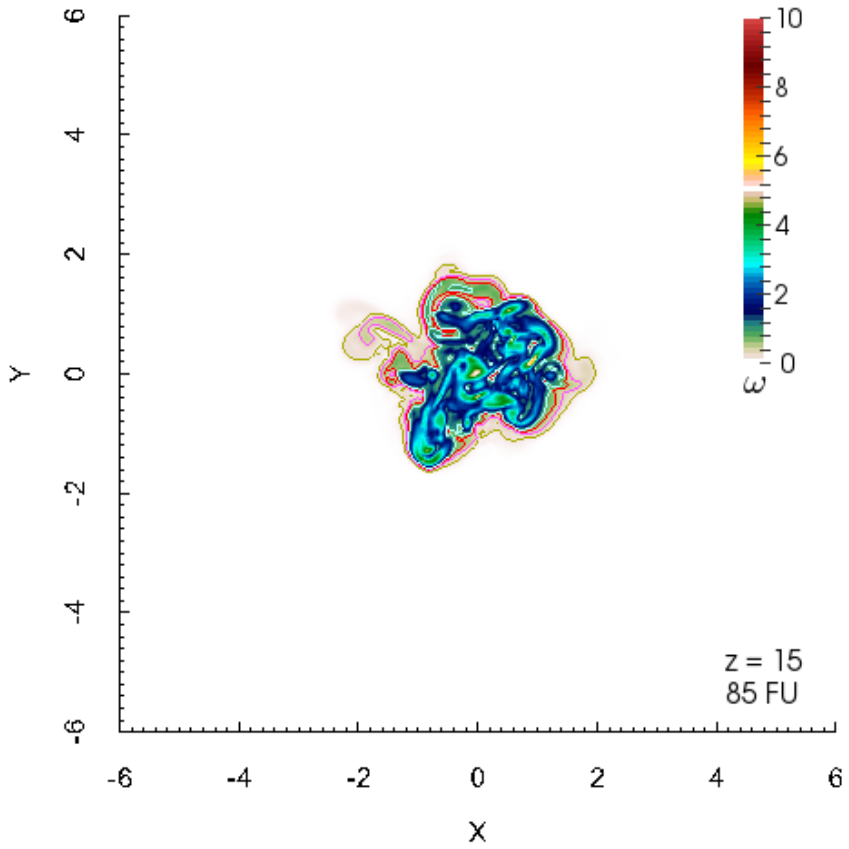
-4
-2
0
2
4
6

Diametral cross-sections

at 85 FU, with z


Y
X
ω
z = 10
85 FU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Y
ω
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0
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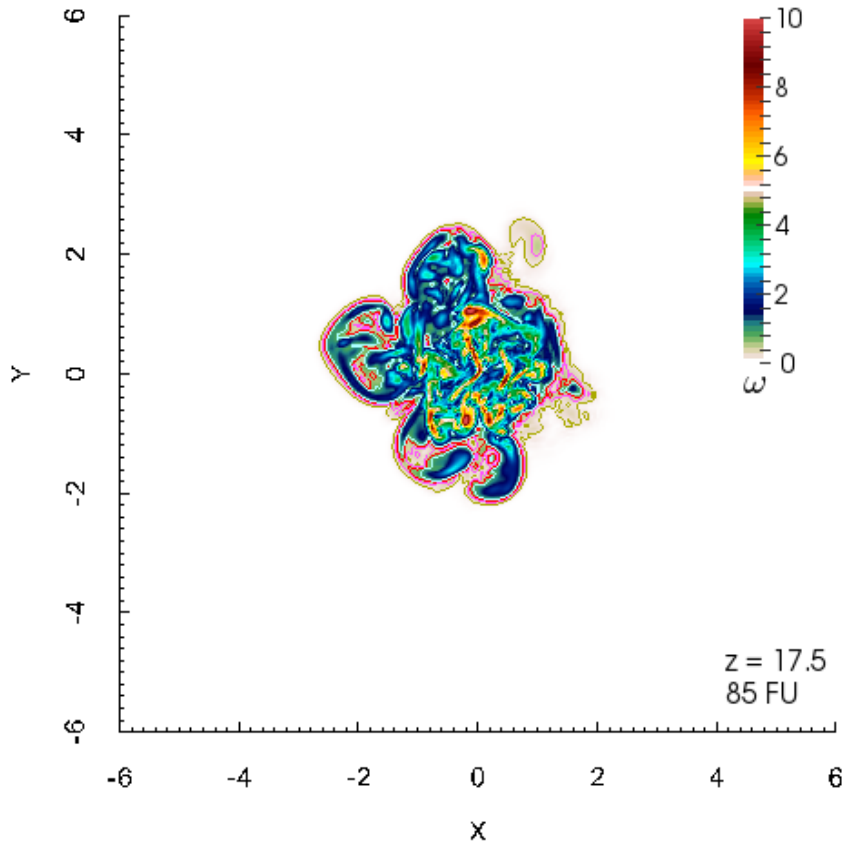
4
6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X
Y
-6
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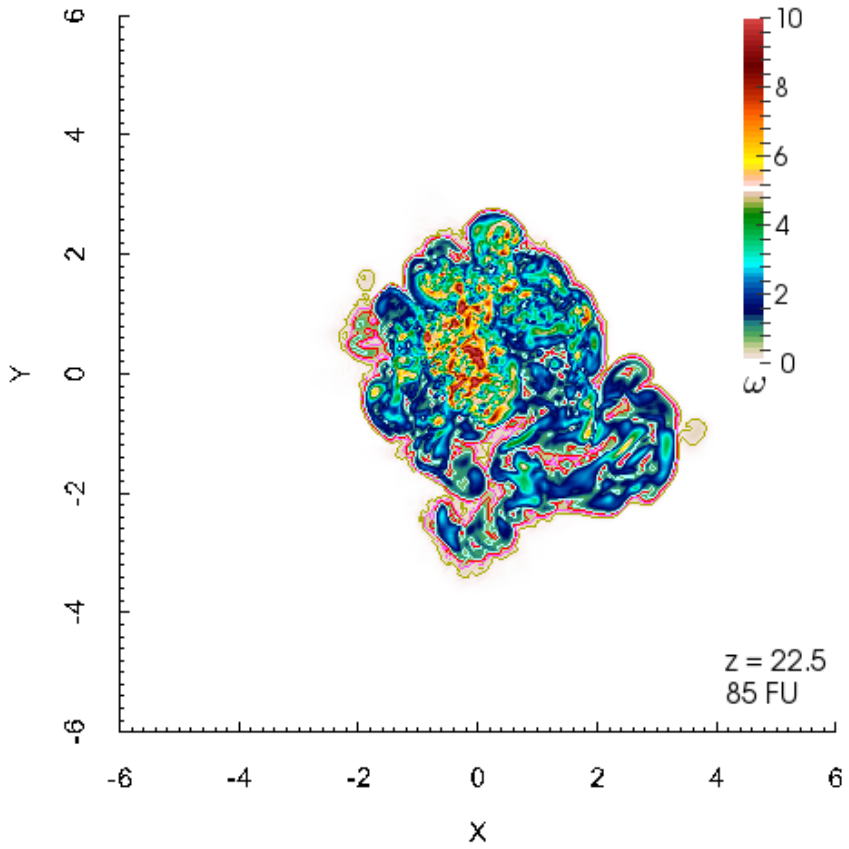
-2
0
2
4
6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85 FU
X
Y
ω
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0
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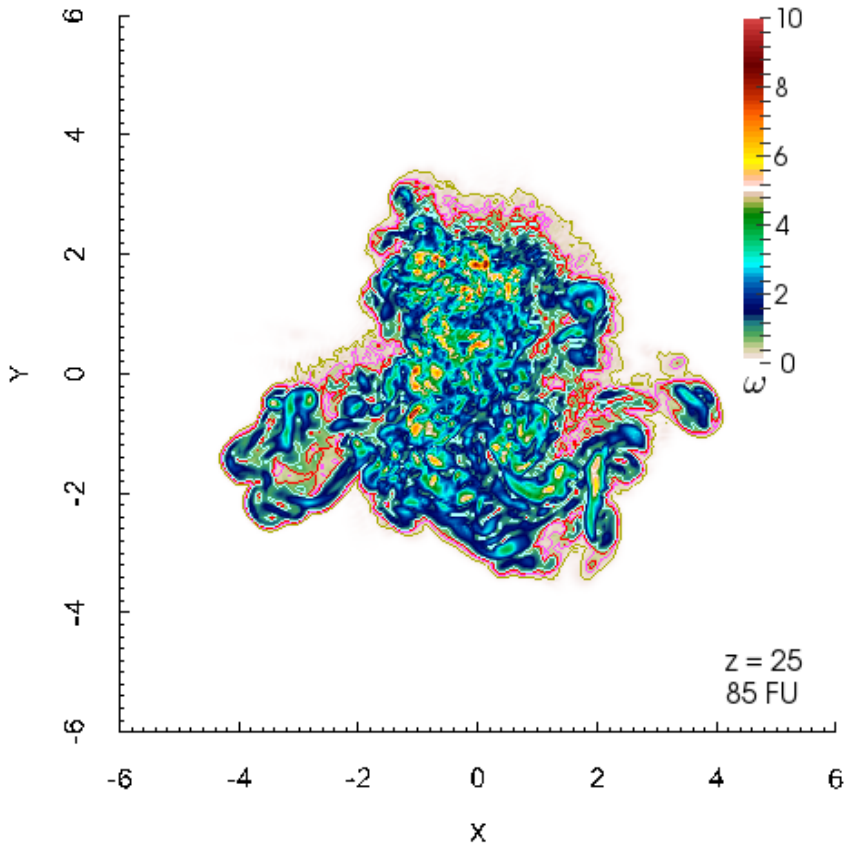
4
6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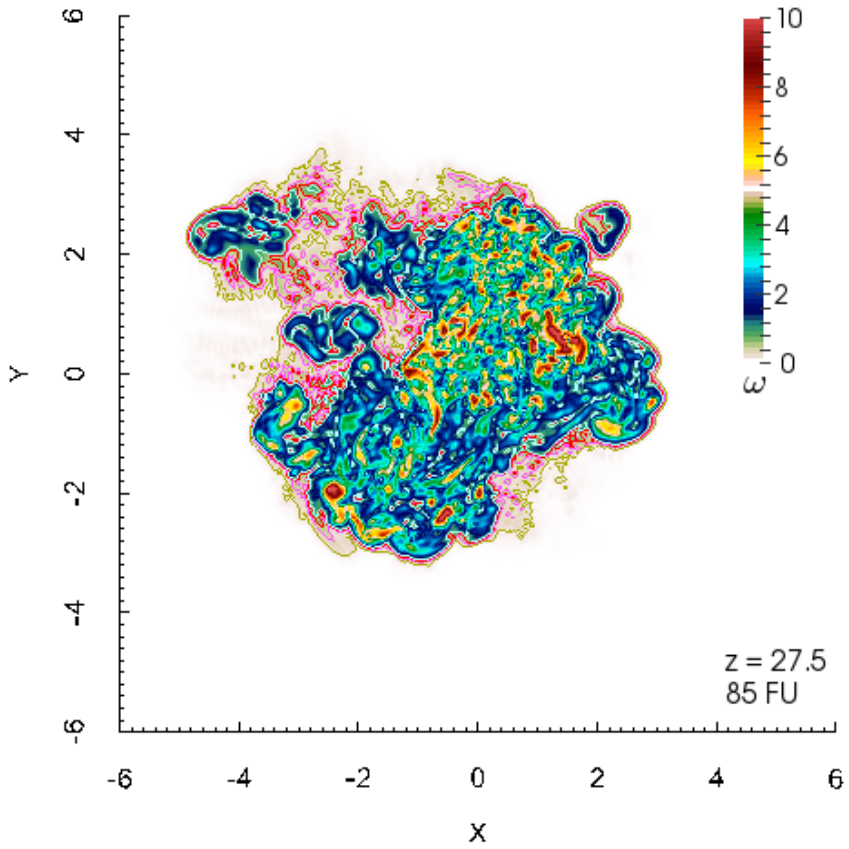
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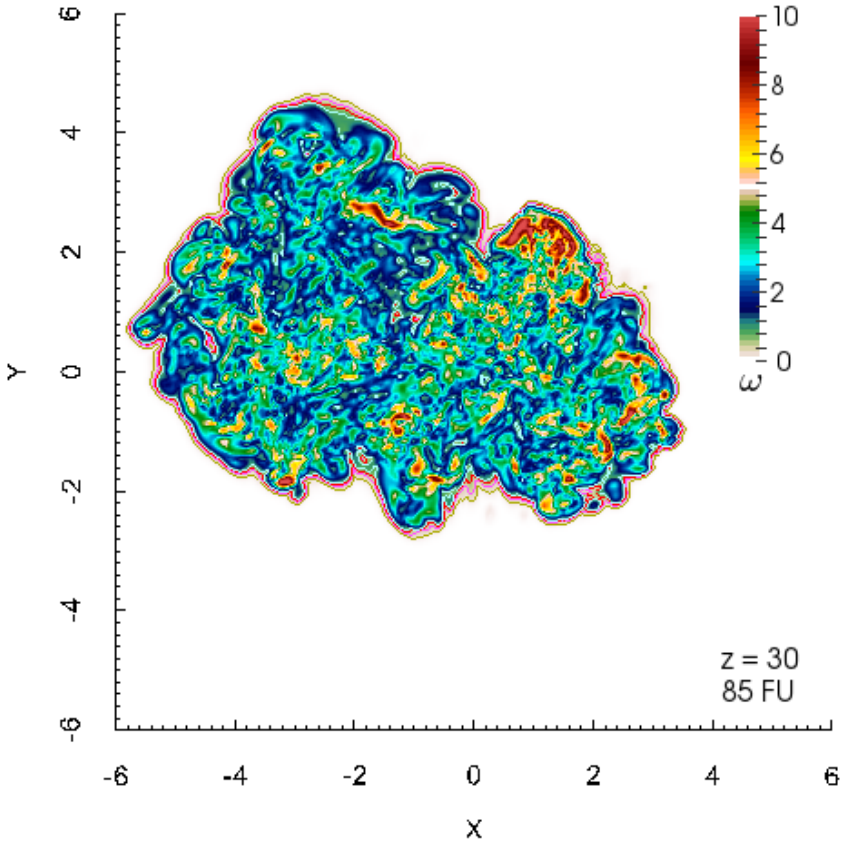
6


z = 30
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X
Y
ω
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0
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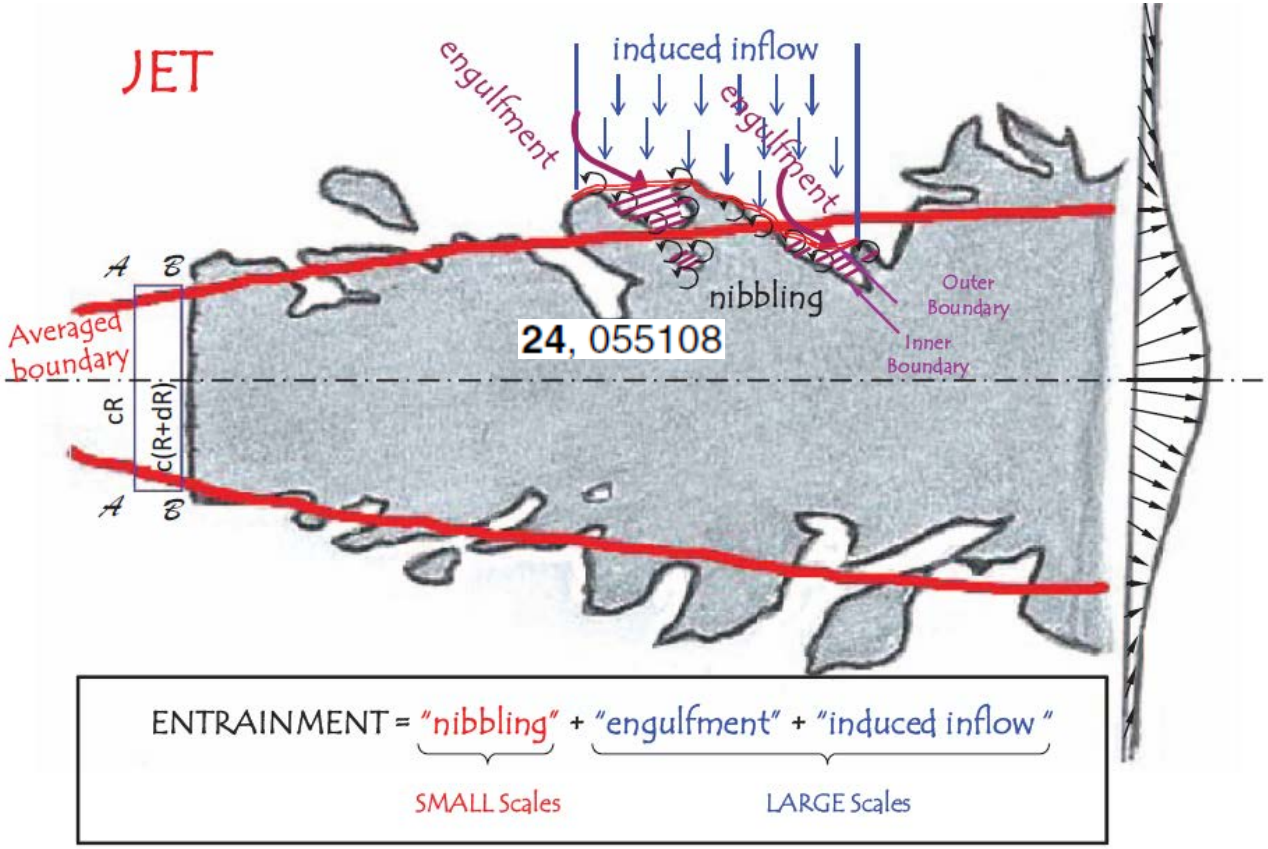
4
6

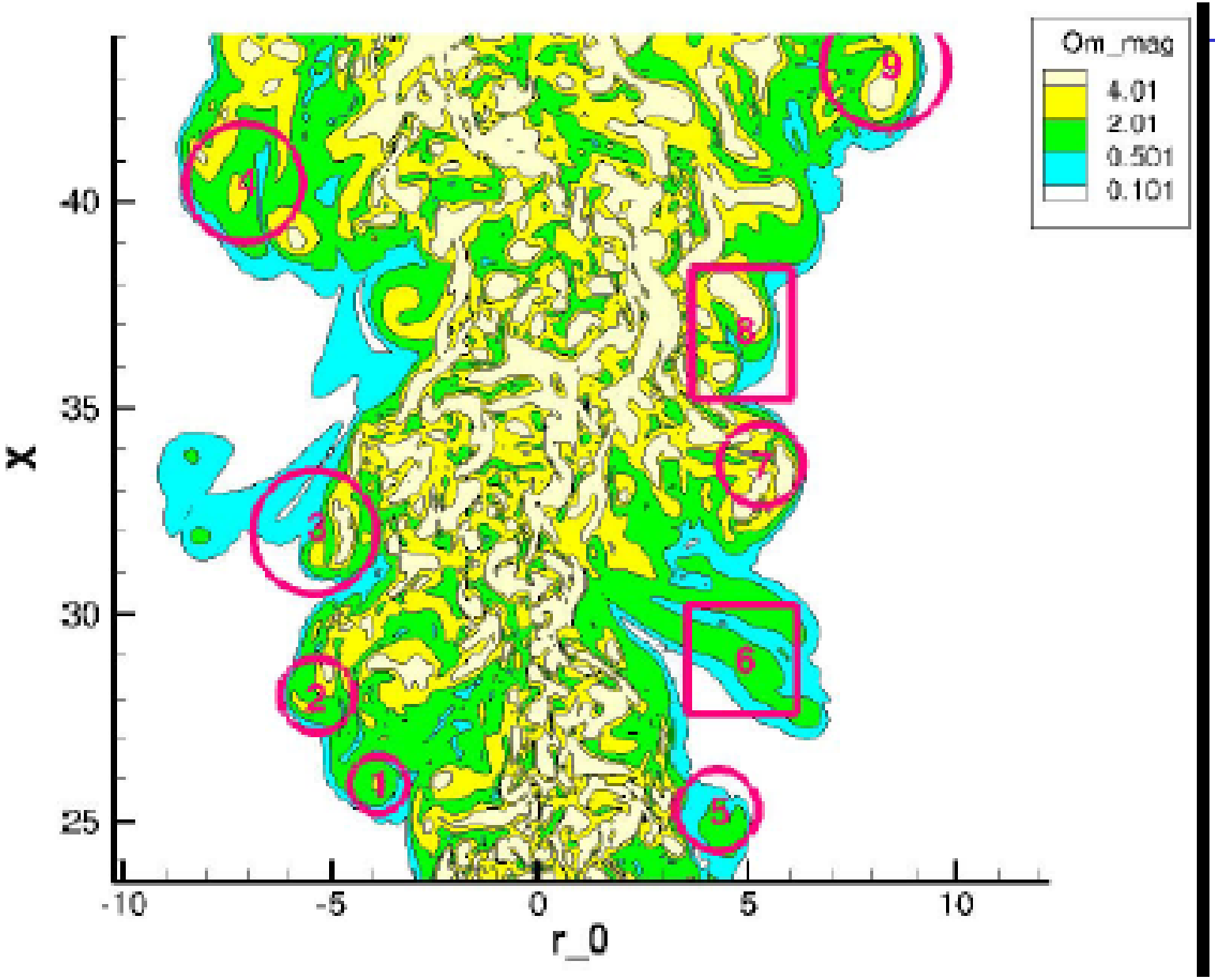
THE ENTRAINMENT PROCESS

ONE VIEW OF ENTRAINMENT

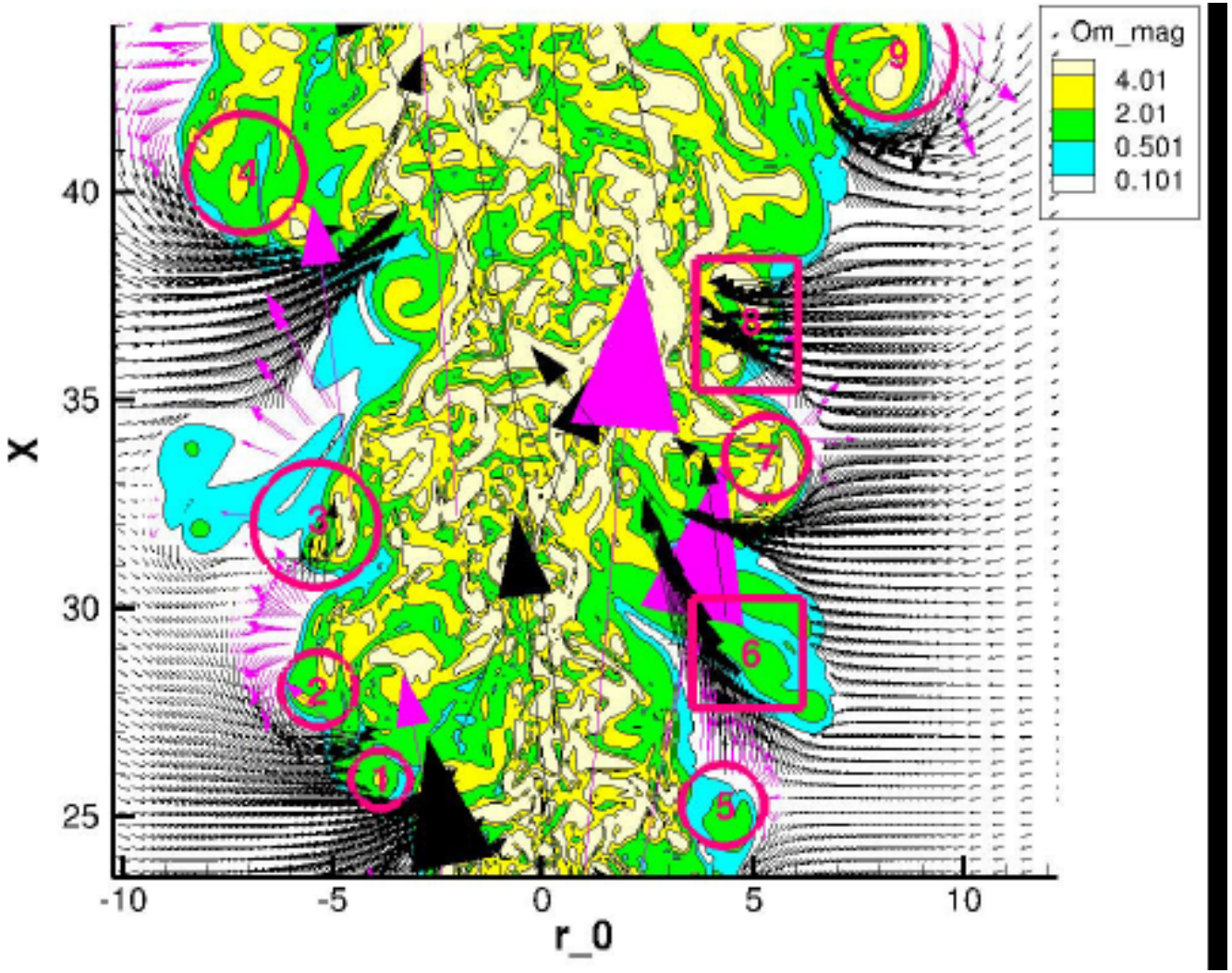


Philip and Marusic, 2012,PoF **24**

AXIAL Section : Vorticity field

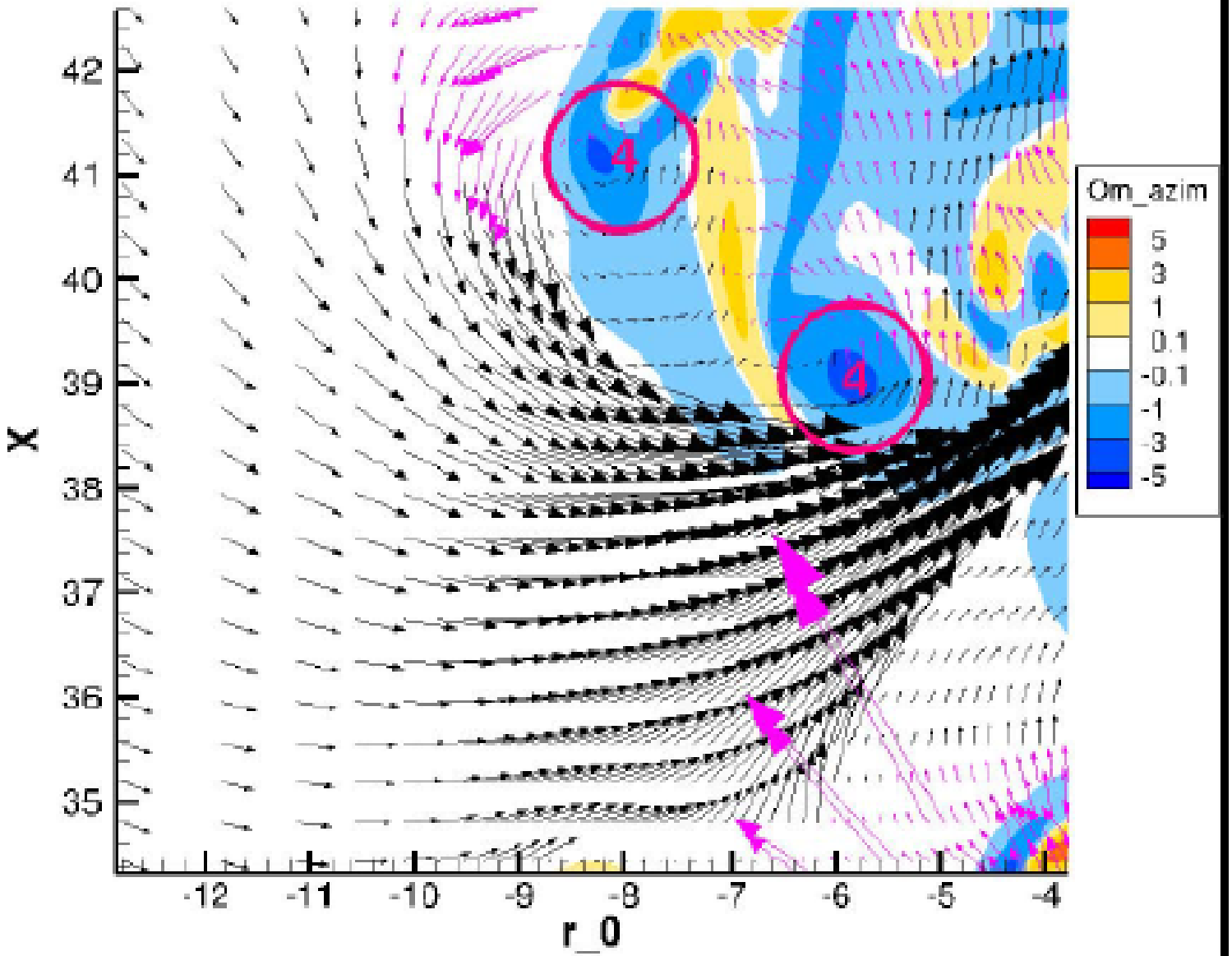


ANOTHER VIEW OF ENTRAINMENT



AXIAL Section : Velocity & Vorticity fields

AZIMUTHAL OMEGA AND INFLOW ACROSS EDGE NEAR JET BOUNDARY



PROPOSED VIEW OF THE ENTRAINMENT PROCESS

- Largely episodic in both time and space . . .
- . . . with local inrush events, – induced in the ambient outer fluid by neighbouring vorticity elements of coherent structures within the core flow, –. . .
- . . . often pushing the turbulent / non-turbulent (T/NT) boundary into a deep, convoluted interface (~ ‘well’) . . .
- . . . creating a strong ‘engulfing event’ . . .
- . . .that culminates in fluid crossing the T/NT interface in the well – through ‘nibbling’ (?).
- Entrainment coefficients vary greatly from Turner’s similarity value and . . .
- . . . are strongly affected by heat release, . . .
- . . . which creates a baroclinic torque . . .

PROPOSED VIEW OF THE ENTRAINMENT PROCESS

- . . . that leads to an explosive growth in vorticity, . . .
- . . .disrupts the coherent structures that would have filled the non-diabatic flow . . .
- . . . and changes the nature of inrush events . . .
- . . . which affects entrainment. . . .
- . . . And so on!

Conclusions

CONCLUSION

- Cumulus clouds are generally transient flows

- Latent heat release on condensation of water vapour changes an ordinary plume into a cloud-like flow

- So a transient diabatic plume seems like a good fluid-dynamical model for cumulus flow

- Measurements in transient diabatic plumes show systematic but wide variations in entrainment coefficient with cloud height. Reason for great variety of proposals made over decades that have all ‘seemed’ based on ‘fact’ ?

- Computer simulations suggest that the
  baroclinic torque drives the cumulus flow engine

Conclusions continued……

- 3D Navier-Stokes-Boussinesq solver capable of simulating cloud flow developed and validated.

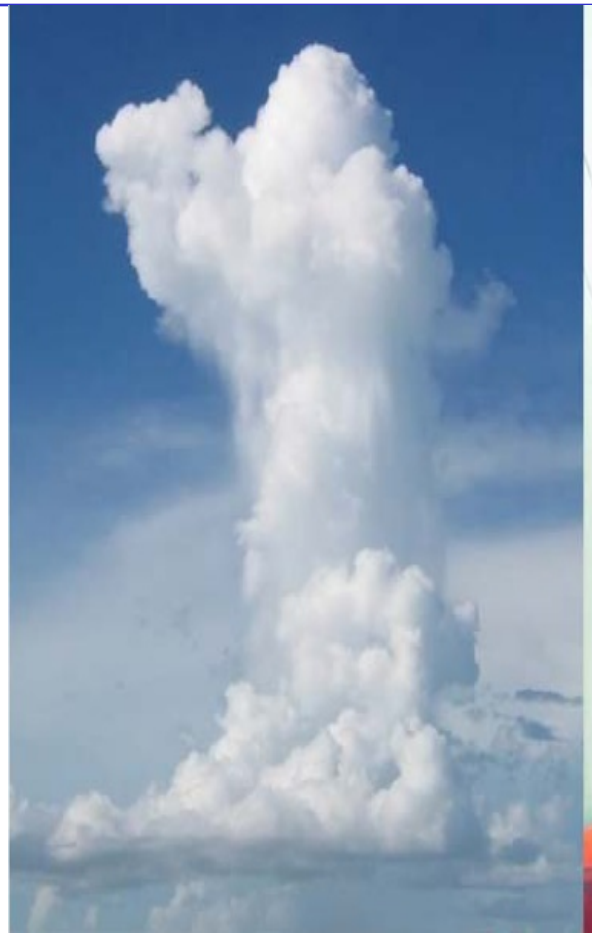
- Significant role played by heating profile history in determining the shape of any cumulus flow.

- Strong effect of off-source buoyancy addition and baroclinic torque on the structure of the flow

- 5 distinct regimes:
  1. A nearly laminar constant width regime
  2. A nearly linearly growing turbulent plume regime
  3. HIZ where the width is nearly constant
  4. A regime of slow growth in width culminating at the maximum
  5. A short dome like cloud top

- Preliminary estimates on the entrainment coefficient.

Real Cloud



NOAA Research, Jim Lee

Laboratory Cloud

RN ++ 2011 *PNAS*

Cyber Cloud

Present Simulation

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