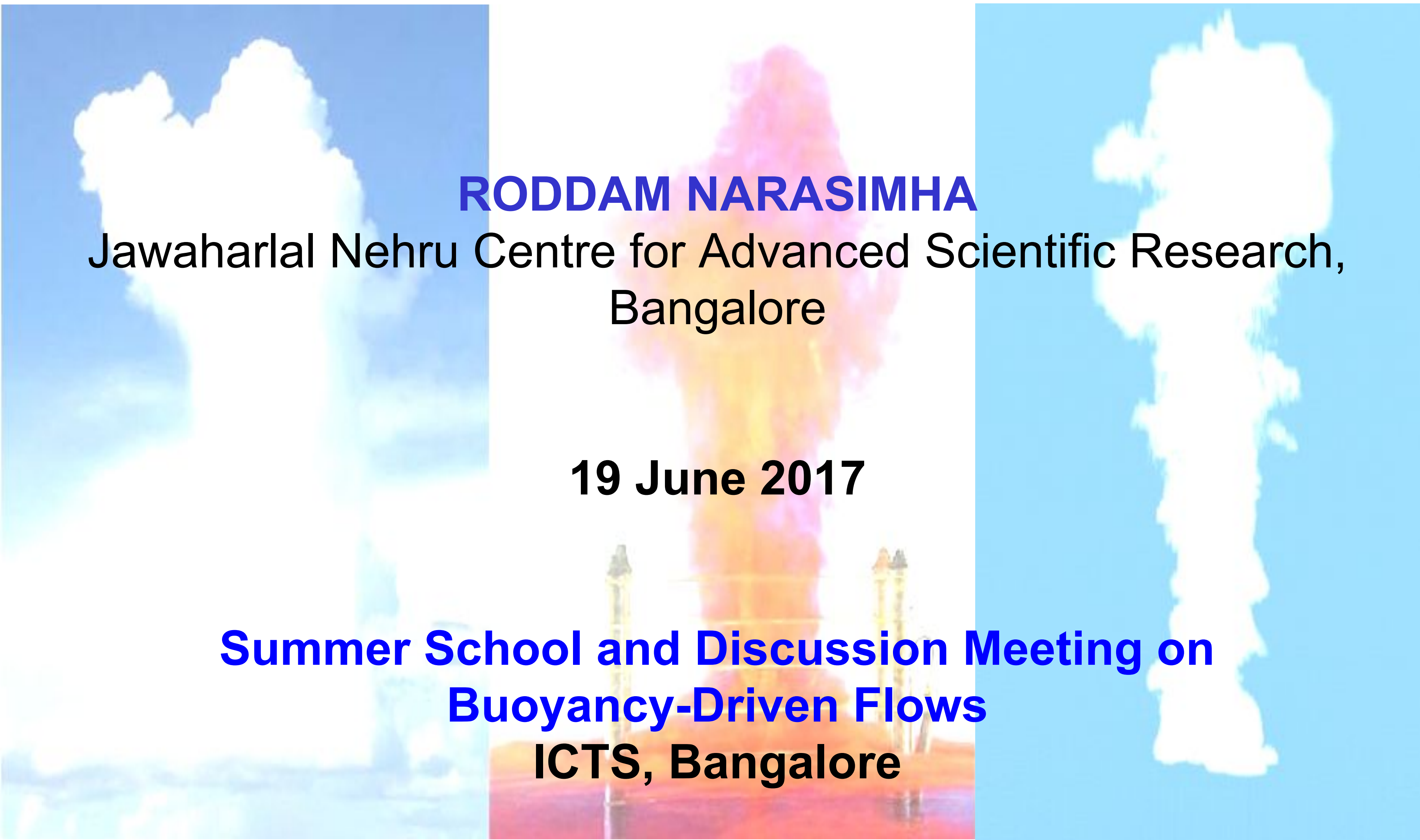
THE FLUID DYNAMICS OF CUMULUS CLOUDS



RODDAM NARASIMHA
Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore

19 June 2017

Summer School and Discussion Meeting on Buoyancy-Driven Flows
ICTS, Bangalore

CLIMATE SCIENCE

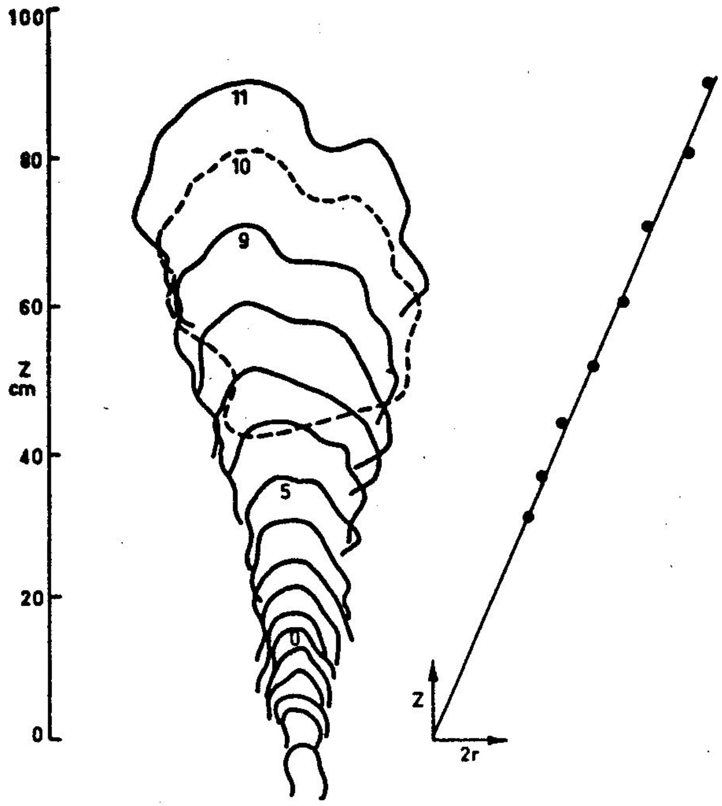
Physicists, your planet needs you

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

BY QUIRIN SCHIERMEIER

Nature Vol. 520, 9 April 2015

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

BOTANIZING CLOUD TYPES

- WMO (1956):
  Cloud: A visible aggregate of minute particles of water or ice, or both, in the free air

- Luke Howard 1772-1864: 10 genera

  Cumulus[1] Cumulo-nimbus
  Stratus[2] Stratocumulus
  Nimbo-stratus Altostratus
  Altocumulus Cirrus[3]
  Cirrostratus Cirrocumulus

  Fog added later as 11th genus.

  Nimbo: rain-bearing Alto: high

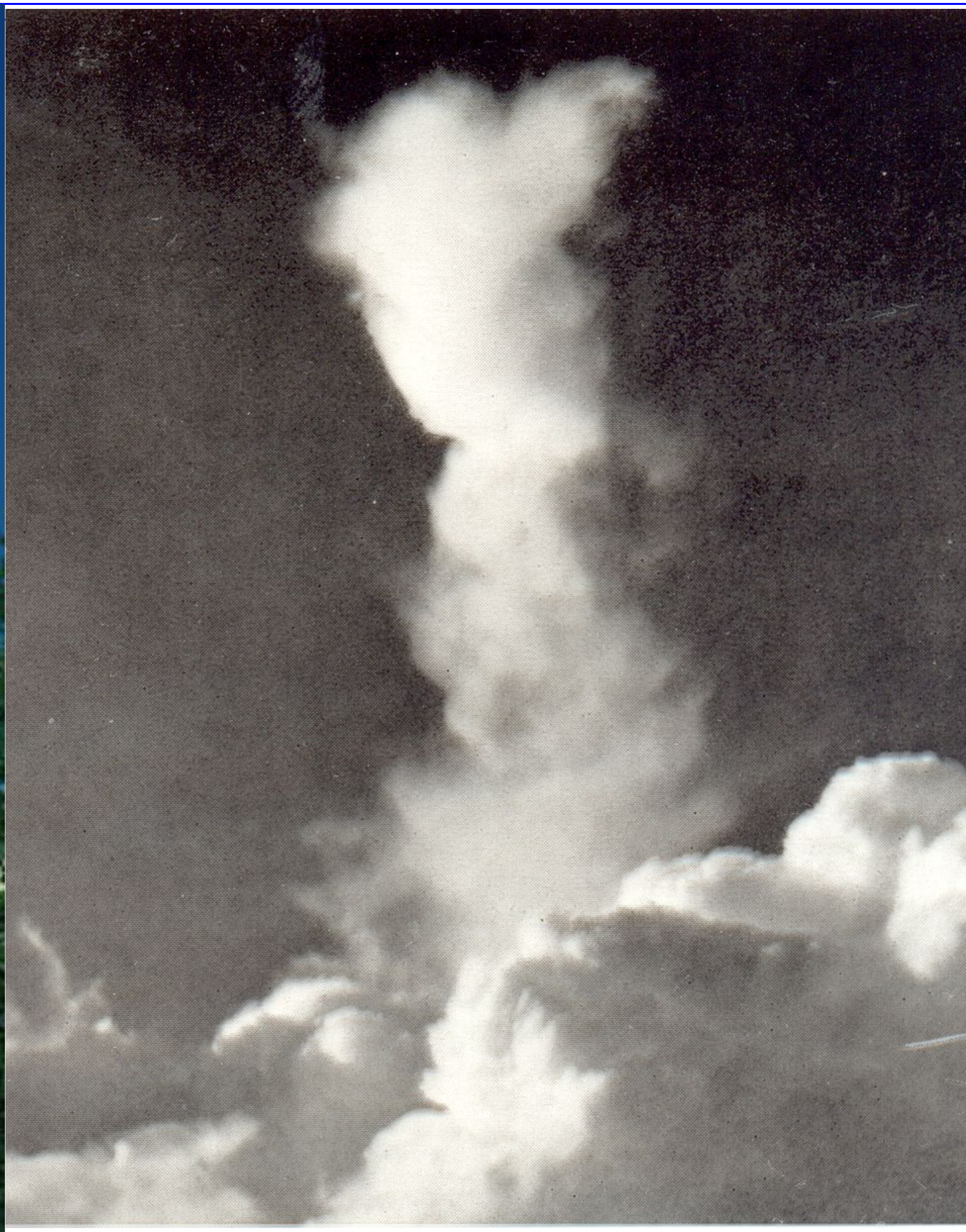
  ---

  [1]3D; heap [2]2D, sheet [3]1D, filament

  # →3 etages → 26 species → 31 varieties

- Marker becomes Player in 1950s: (contra David Brunt 1941)

CUMULUS SHAPES : FLUFFY BALLS, OR SHOOTING PLUMES ? . . .



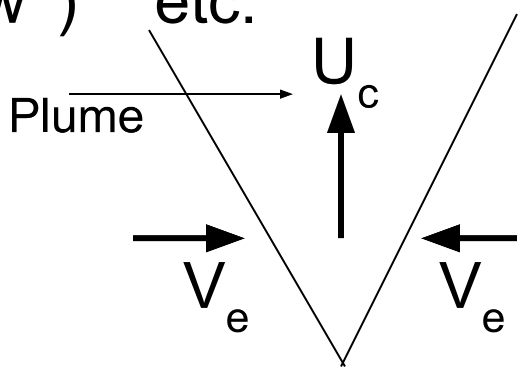
BACKGROUND 1

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

- A central problem in the fluid dynamics of clouds concerns their entrainment characteristics; **entrainment is also the dynamic behind shape**

- Taylor's entrainment hypothesis (1945) for free turbulent shear flows (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 (Turner 1973, 1986 JFM)



BACKGROUND 2

❖ Does not work for cumulus clouds – which are not fans or cones, but heaps and the hot cumulus towers of Riehl (58).

❖ 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”.

CUMULUS CLOUDS

can be

shallow / deep

fluffy / smooth

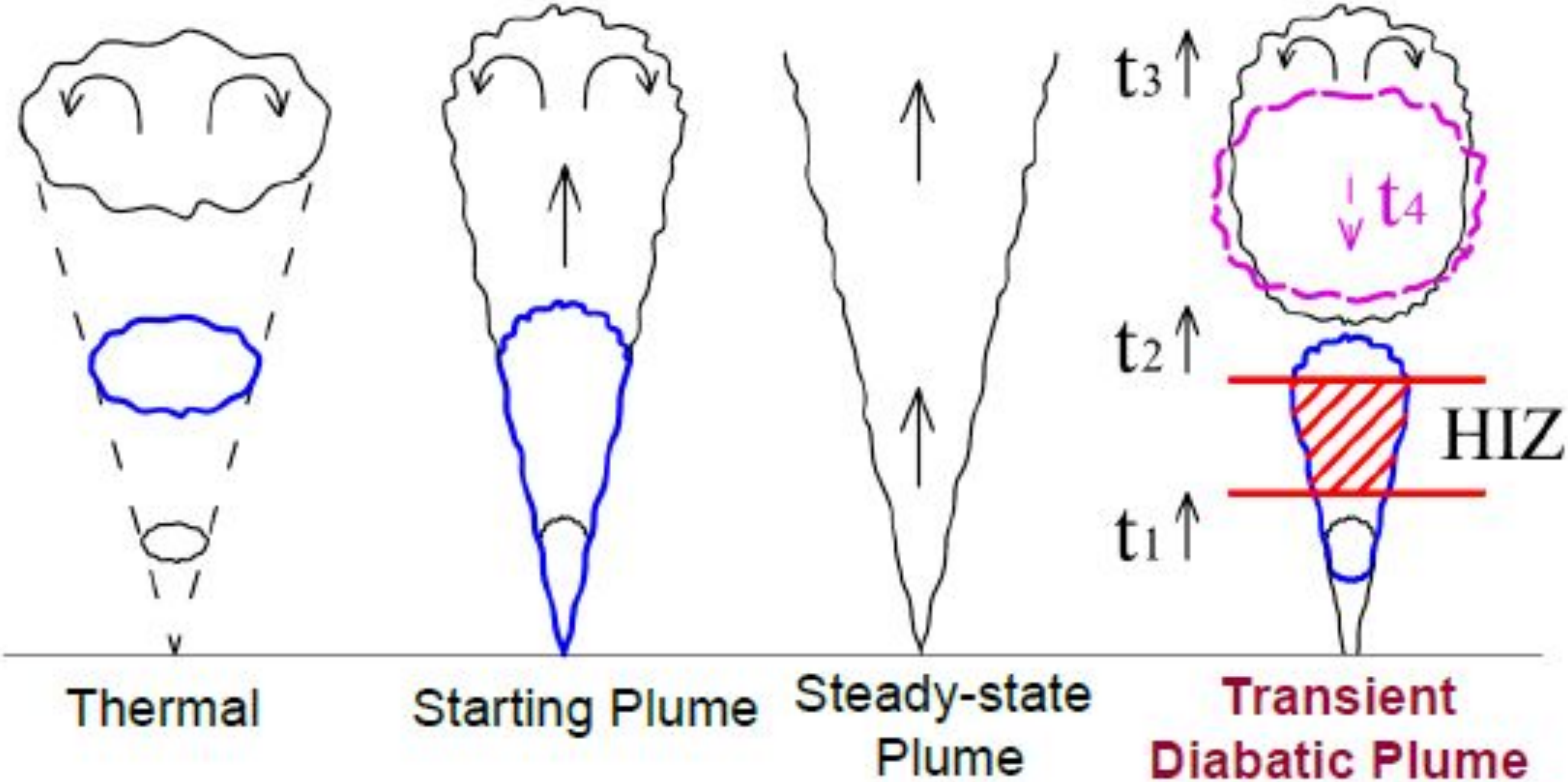
boiling / fading

loners /crowded

chaotic / ordered

BUT THEY ARW ALL FLOW CLOUDS

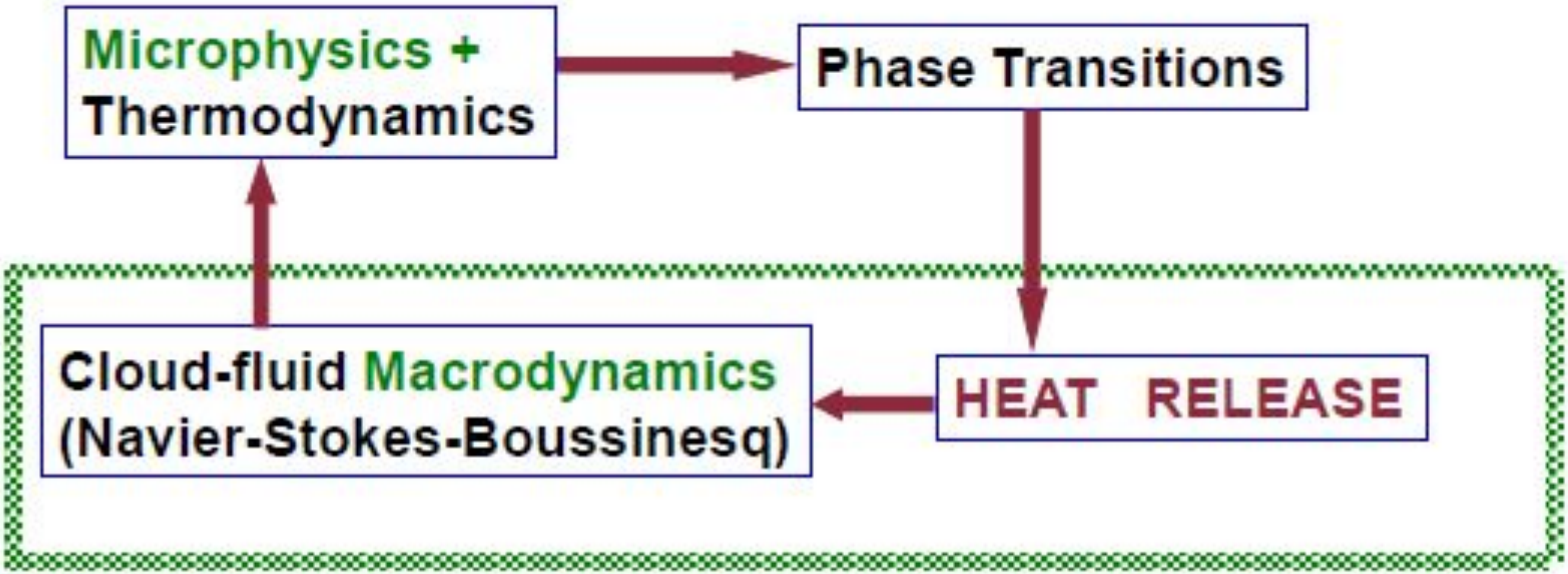
PHYSICAL FLOW MODELS



Turner's proposals

RN ++ 2011 *PNAS*

FIRST ORDER NON-PRECIPITATING CUMULUS SYSTEM



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)

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

(energy)

Basu, RN 1999 *J. Fluid Mech.*

VORTICITY IN BOUSSINESQ CLOUD

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

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

Basu, RN 1999 *J. Fluid Mech.*

NON-DIMENSIONAL (GLOBAL) HEAT RELEASE PARAMETER

$$G \sim \frac{g\beta}{\rho_o C_p} \frac{Q}{bU^3} \qquad \text{(global)}$$

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/m3) 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)

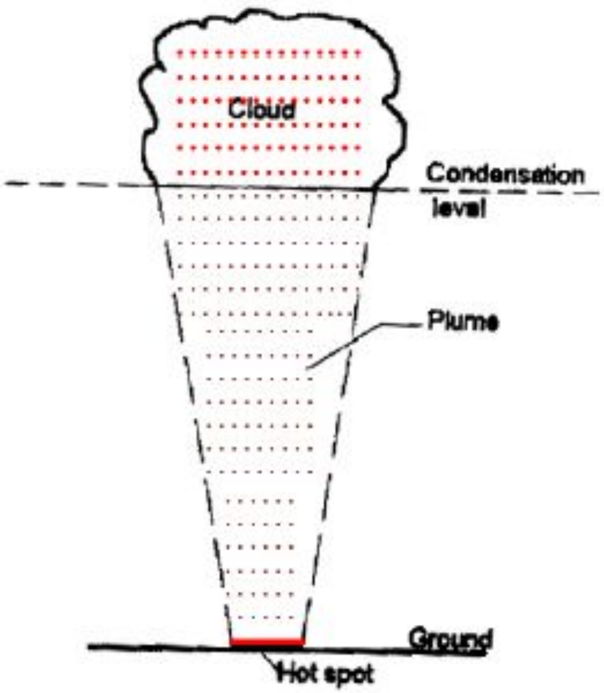
Heat release in general varies in space and time, so define a 'local' heat release number

$$G'(\boldsymbol{x},t) = \frac{g\beta}{\rho_o C_p} \frac{b^2}{U^3} J(\boldsymbol{x},t)$$

Bhat+RN 1996, *JFM*

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

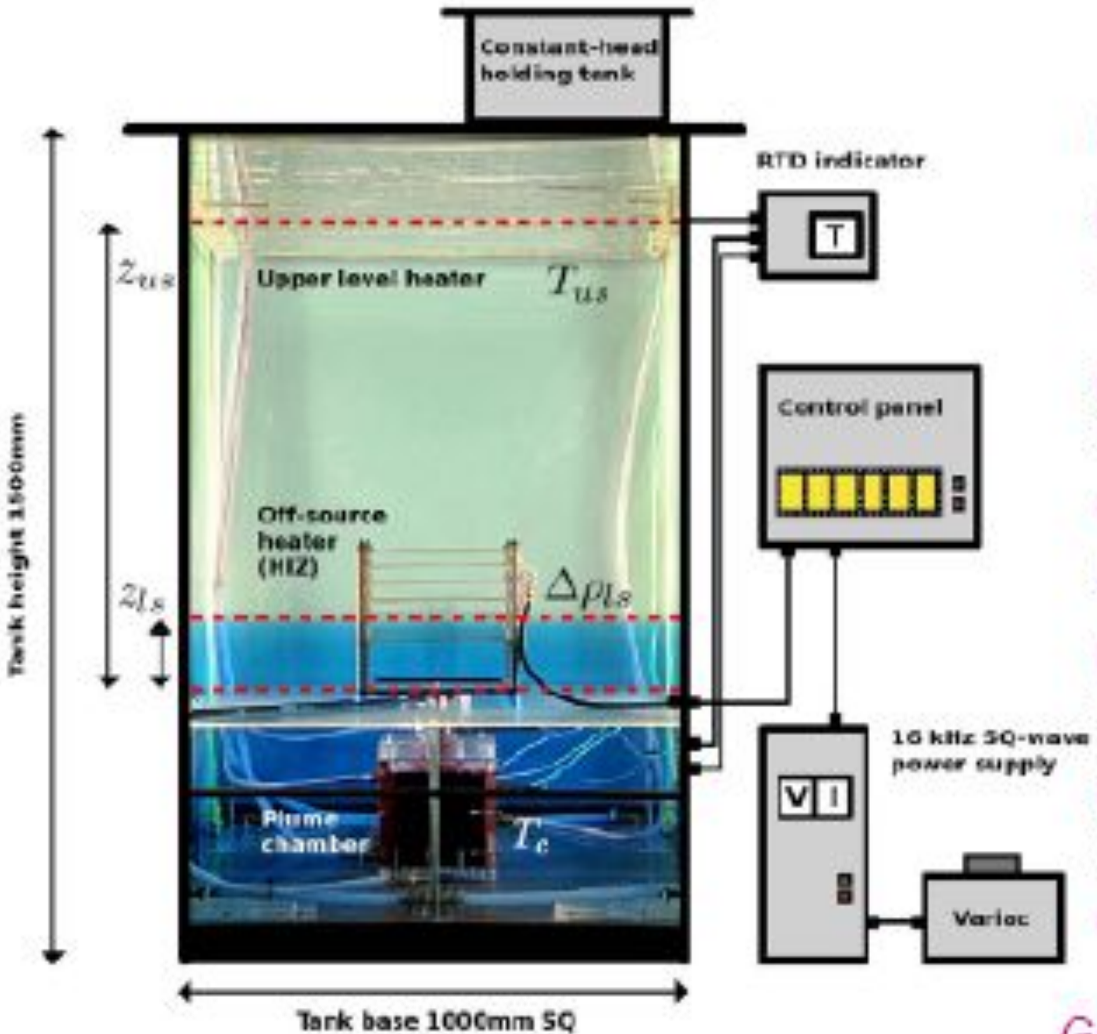
2. We work with *water, not moist air.*

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

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

EXPERIMENTAL SETUP

Experimental Setup



RTD: Resistance Temperature Detector

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

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

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

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)

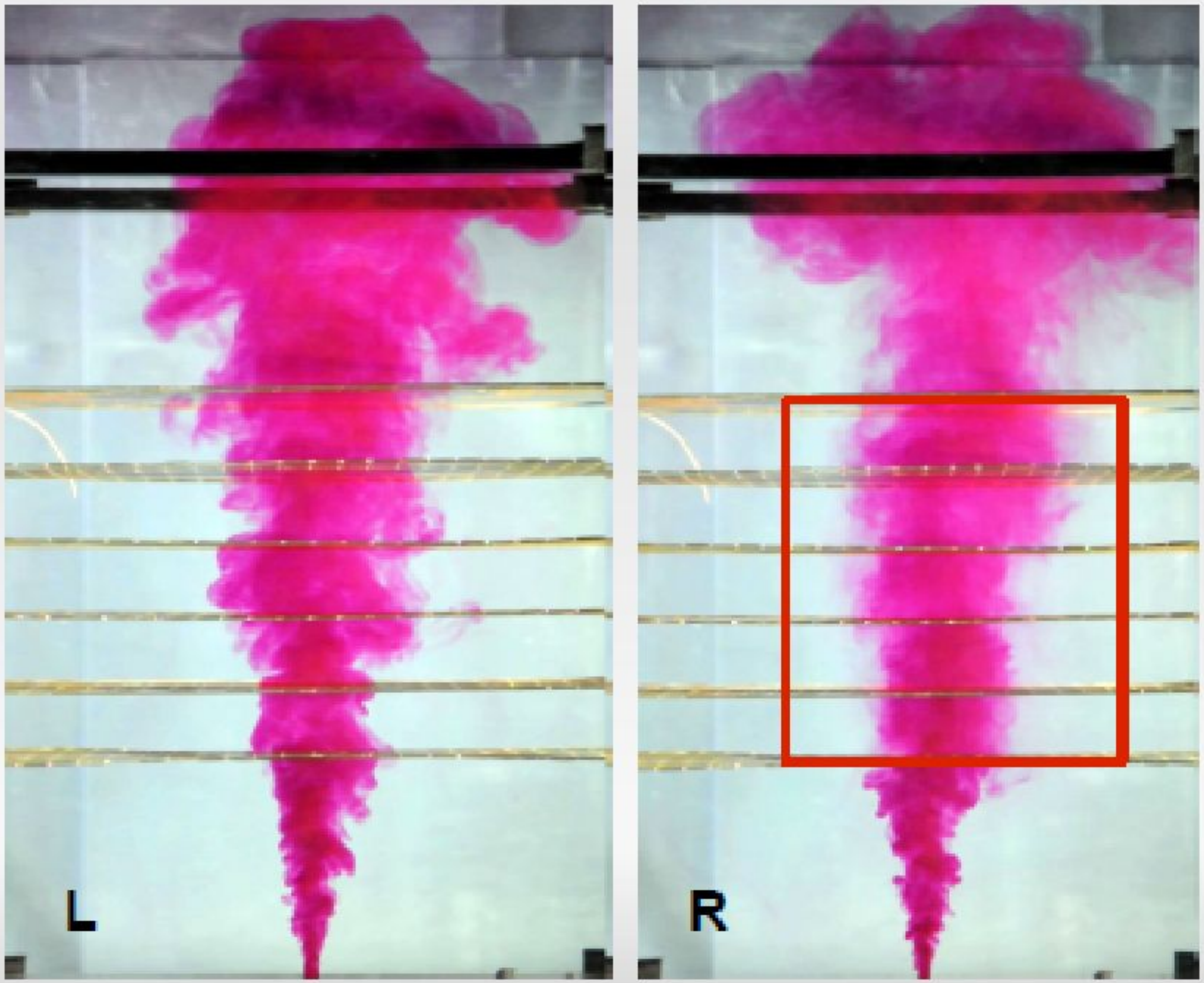
Dynamical similarity: Cloud-like flows in a water tank

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	21×10^{-3}	38×10^{-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

Whole-field visualisation: Temporal evolution of a *starting plume*



- *Re* = 1900
- Exit velocity at nozzle = 0.28 m/s
- ΔT = 25° C (heating chamber)

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

R) $Q = 800\ W$
$G = 8.18$

Heat injection zone

COMPARISON WITH REAL CLOUDS

Classification as per the International Cloud Atlas (WMO)

Based mainly on appearance

Three genera and three species simulated

Genera: Cumulus

Alto- / Strato- cumulus

Species: Congestus

Mediocris

Fractus

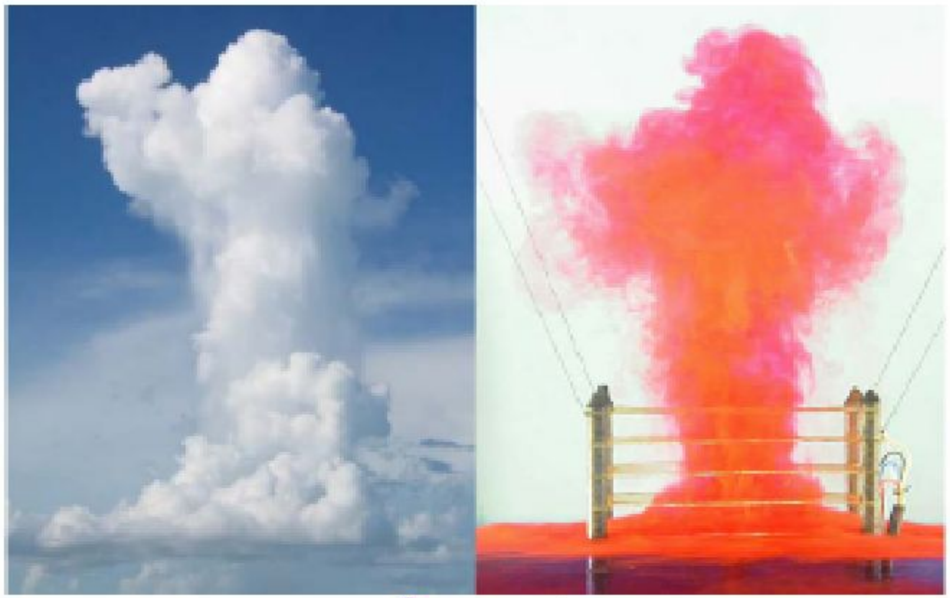
COMPARISON WITH REAL CLOUDS
Towers and Flowers

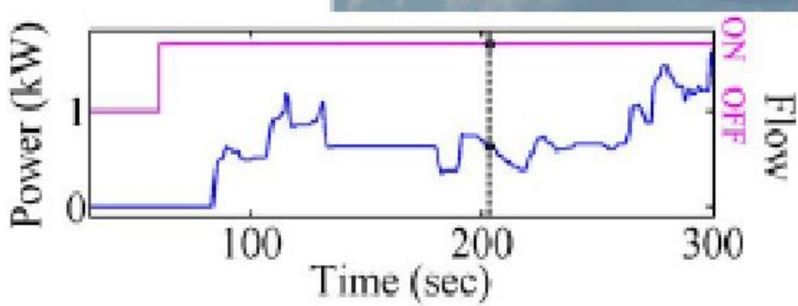
Comparison

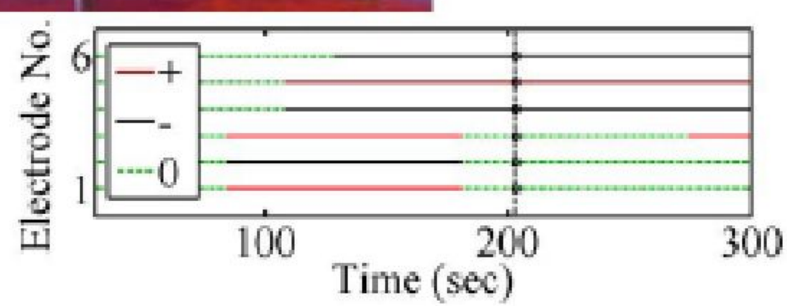
Cumulus Congestus

Tall, narrow,

tower-like







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

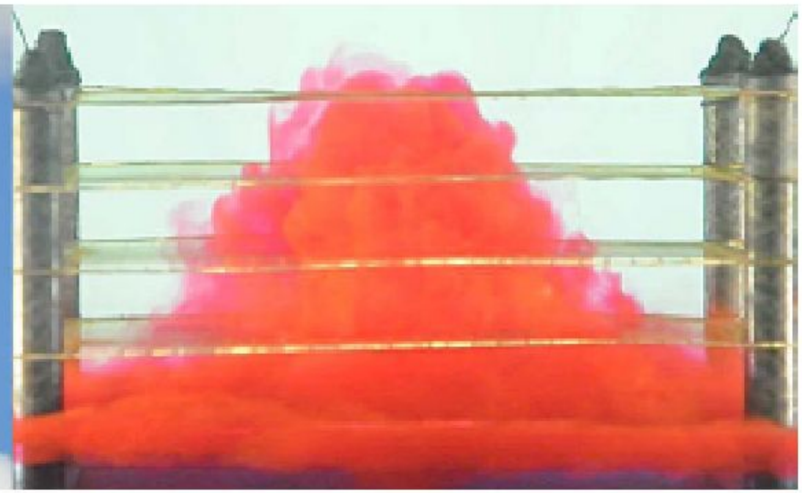
Real Cloud Photo Credit: http://img.photobucket.com/albums/v493/scubastza/Blog%20Stuff/cloud.jpg

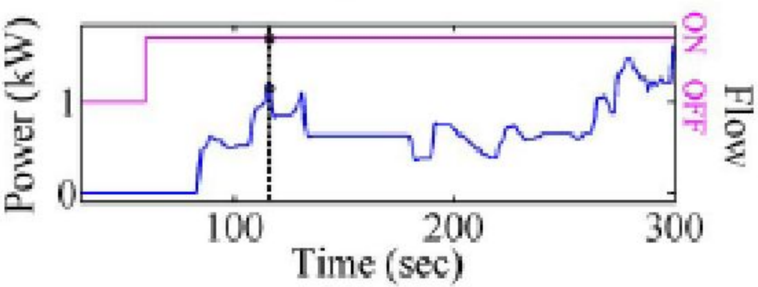
COMPARISON WITH REAL CLOUDS

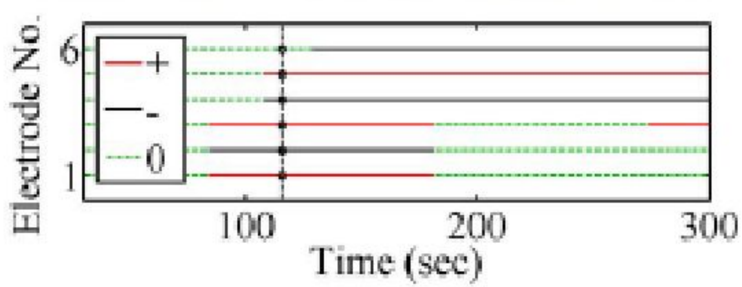
Comparison

Cumulus Congestus

Striking Resemblance







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

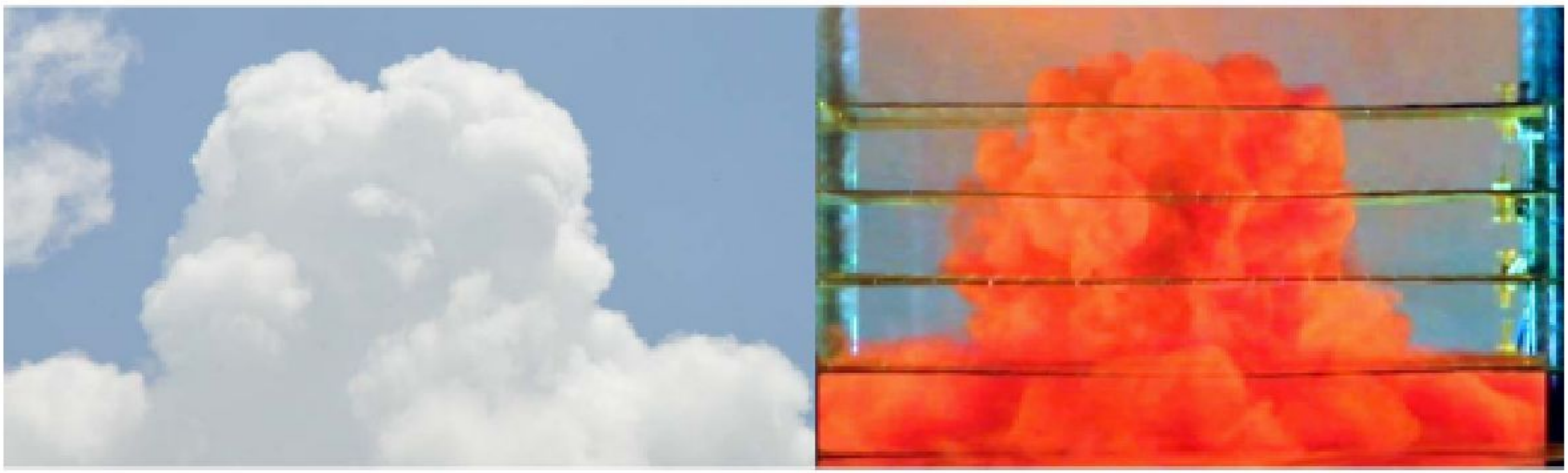
Fluffy, sharp edges, flower-like

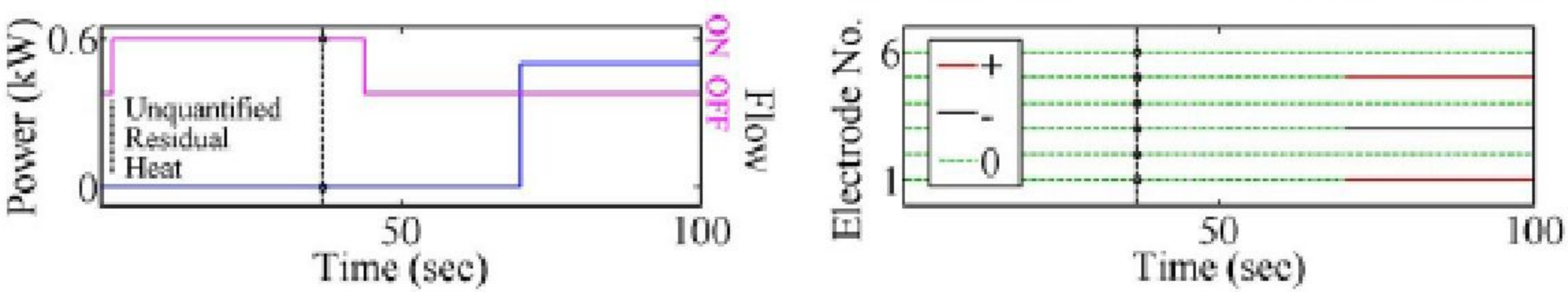
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Congestus

Different Shapes

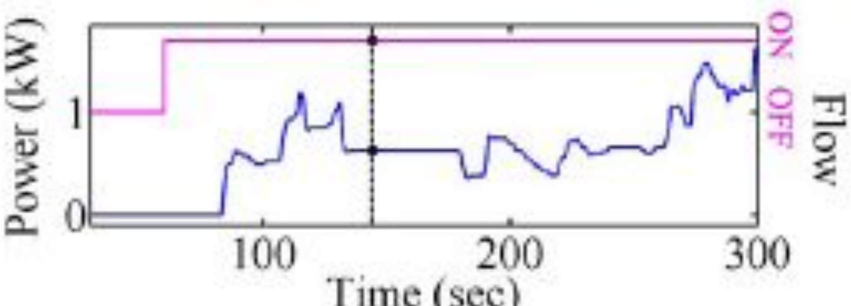


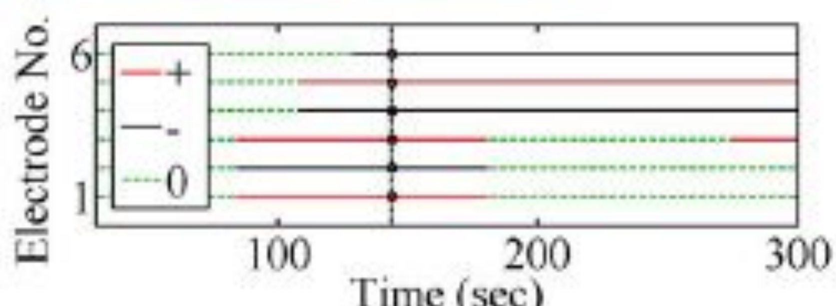


$Re \approx 3000$	$T_c = 25^o\mathrm{C}$	$T_{us} = 28^o\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 145\mathrm{mm}$	$z_{us} = 980\mathrm{mm}$

COMPARISON WITH REAL CLOUDS

Comparison — Cumulus Congestus

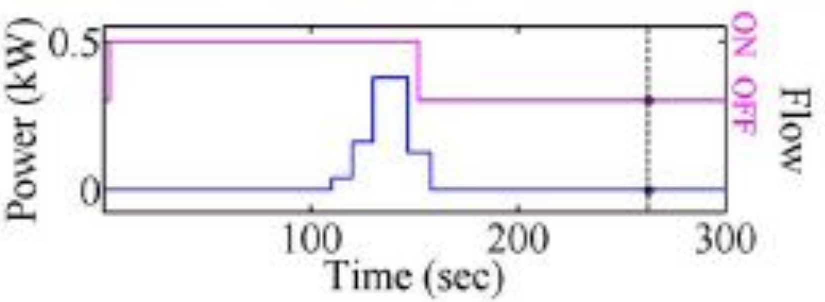


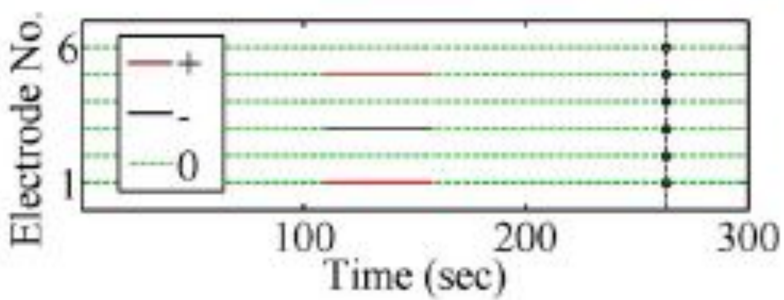


$Re \approx 3000$	$T_c = 30.8°\mathrm{C}$	$T_{us} = 33.9°\mathrm{C}$	$\Delta\rho_{ls} \approx 1\mathrm{kg/m^3}$	$z_{ls} = 126.5\mathrm{mm}$	$z_{us} = 869\mathrm{mm}$

COMPARISON WITH REAL CLOUDS

Comparison   Cumulus Mediocris



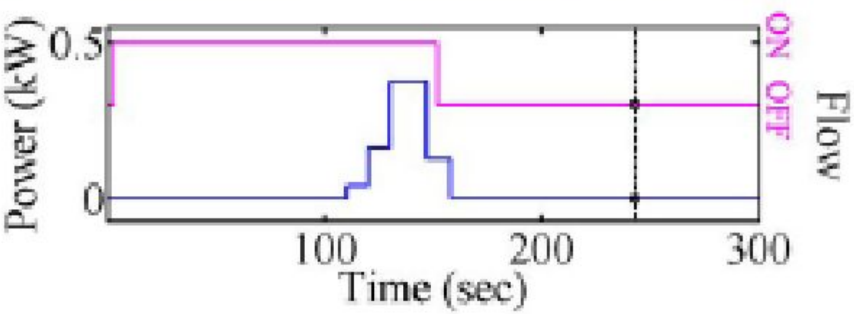


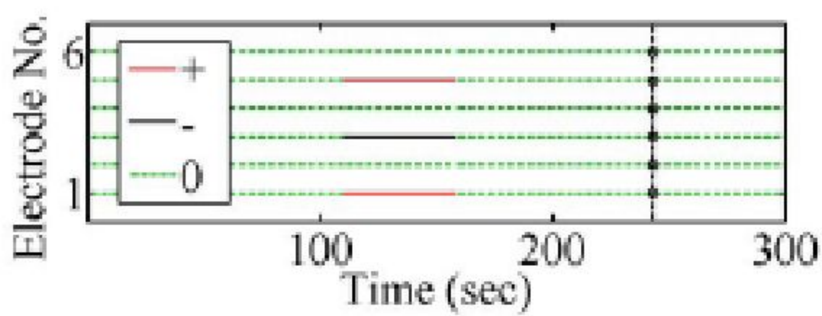
$Re = 560$	$T_c = 25^oC$	$T_{us} = 28^oC$	$\Delta\rho_{ls} \approx 1kg/m^3$	$z_{ls} = 145mm$	$z_{us} = 980mm$

Hovering (slowly sinking), Evaporating

COMPARISON WITH REAL CLOUDS

Comparison | Cumulus Mediocris





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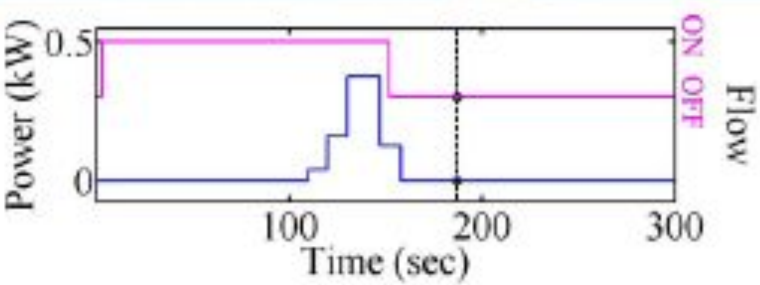
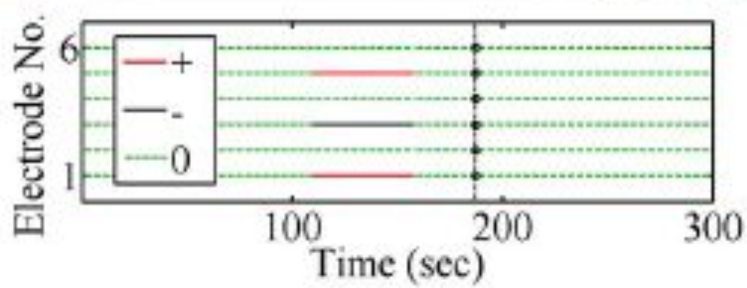
COMPARISON WITH REAL CLOUDS

Comparison

Cumulus Fractus



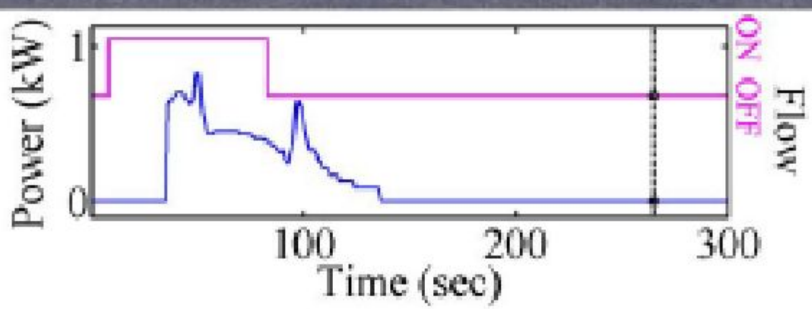


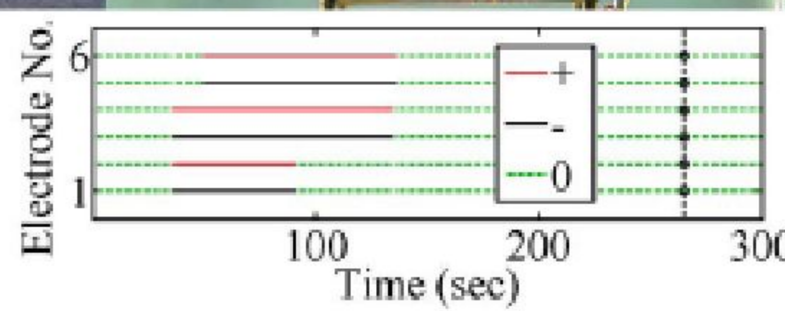
$Re = 560$	$T_c = 25^oC$	$T_{us} = 28^oC$	$\Delta\rho_{ls} \approx 1\text{kg/m}^3$	$z_{ls} = 145\text{mm}$	$z_{us} = 980\text{mm}$

Jagged edges, dissolving stage

COMPARISON WITH REAL CLOUDS

Comparison | Cumulus Fractus





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

Scud, seen during monsoons

Real Cloud Photo Credit: Scorer Plate 43

COMPARISON WITH REAL CLOUDS

- The important parameters identified

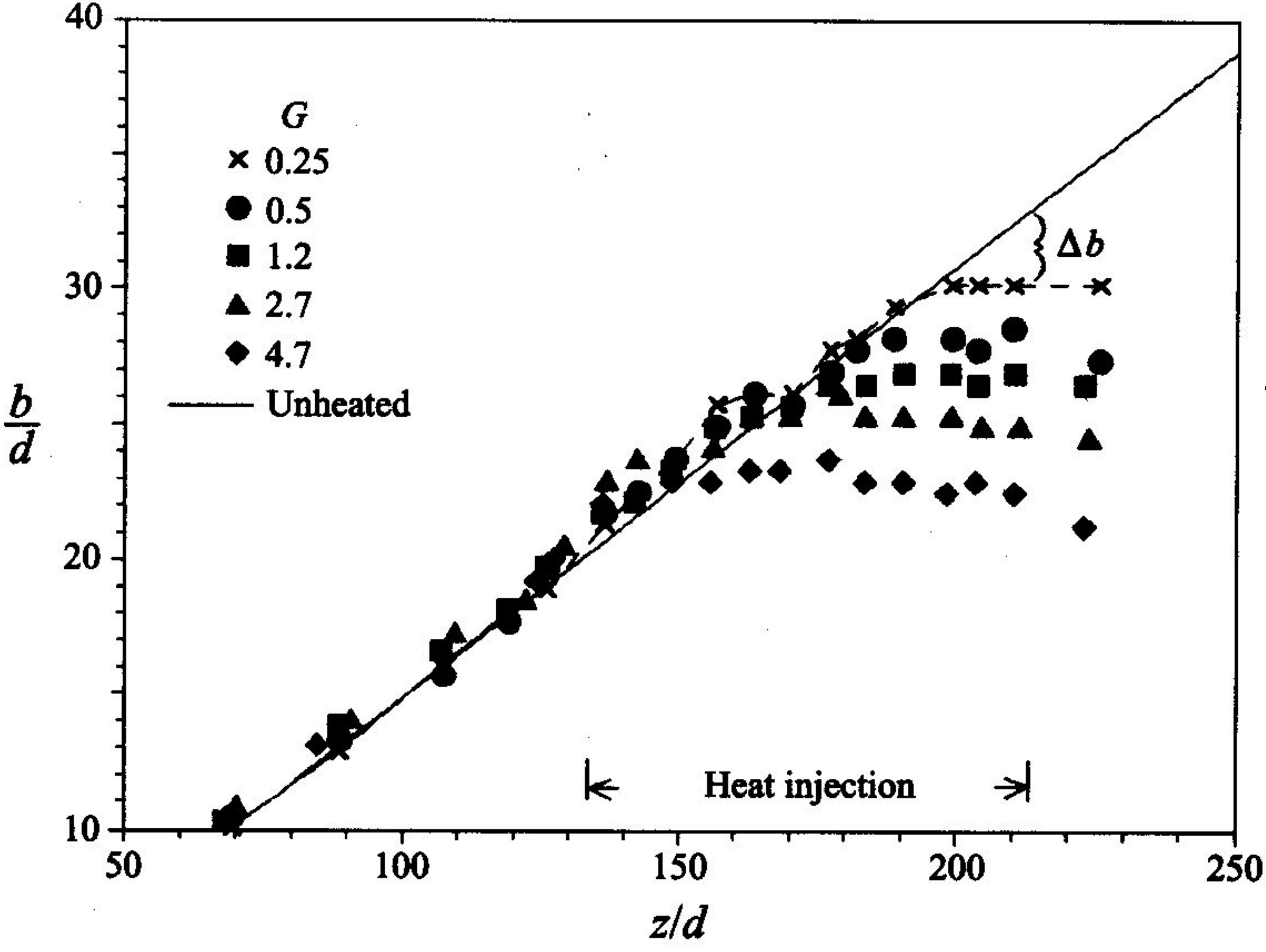
  1. Flow history
  2. Heating profile history
  3. Lower and upper stratification (heights and magnitudes)
  4. Source momentum / buoyancy flux

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

Measurements on a

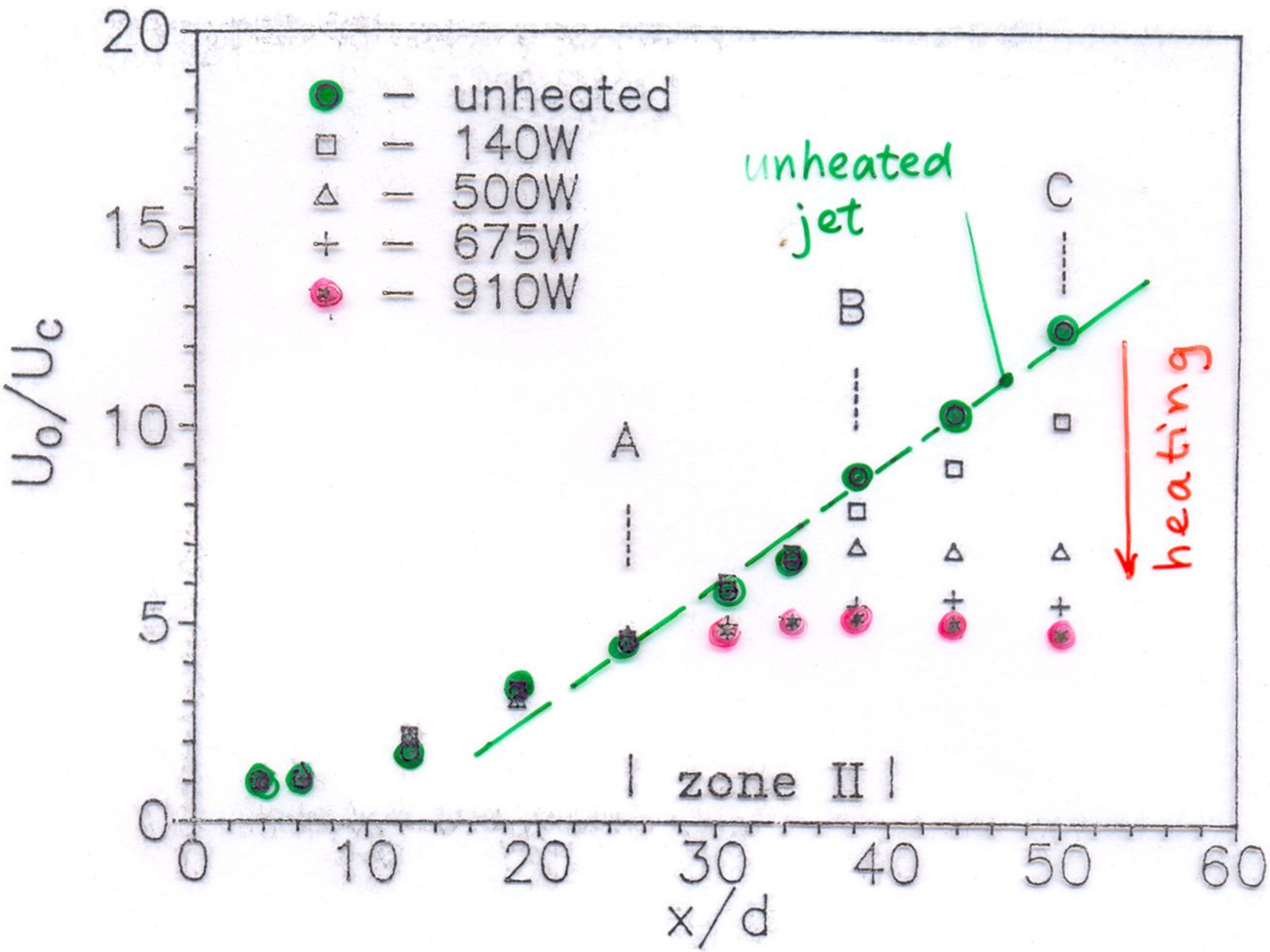
Steady Diabatic Jet

JET WIDTH



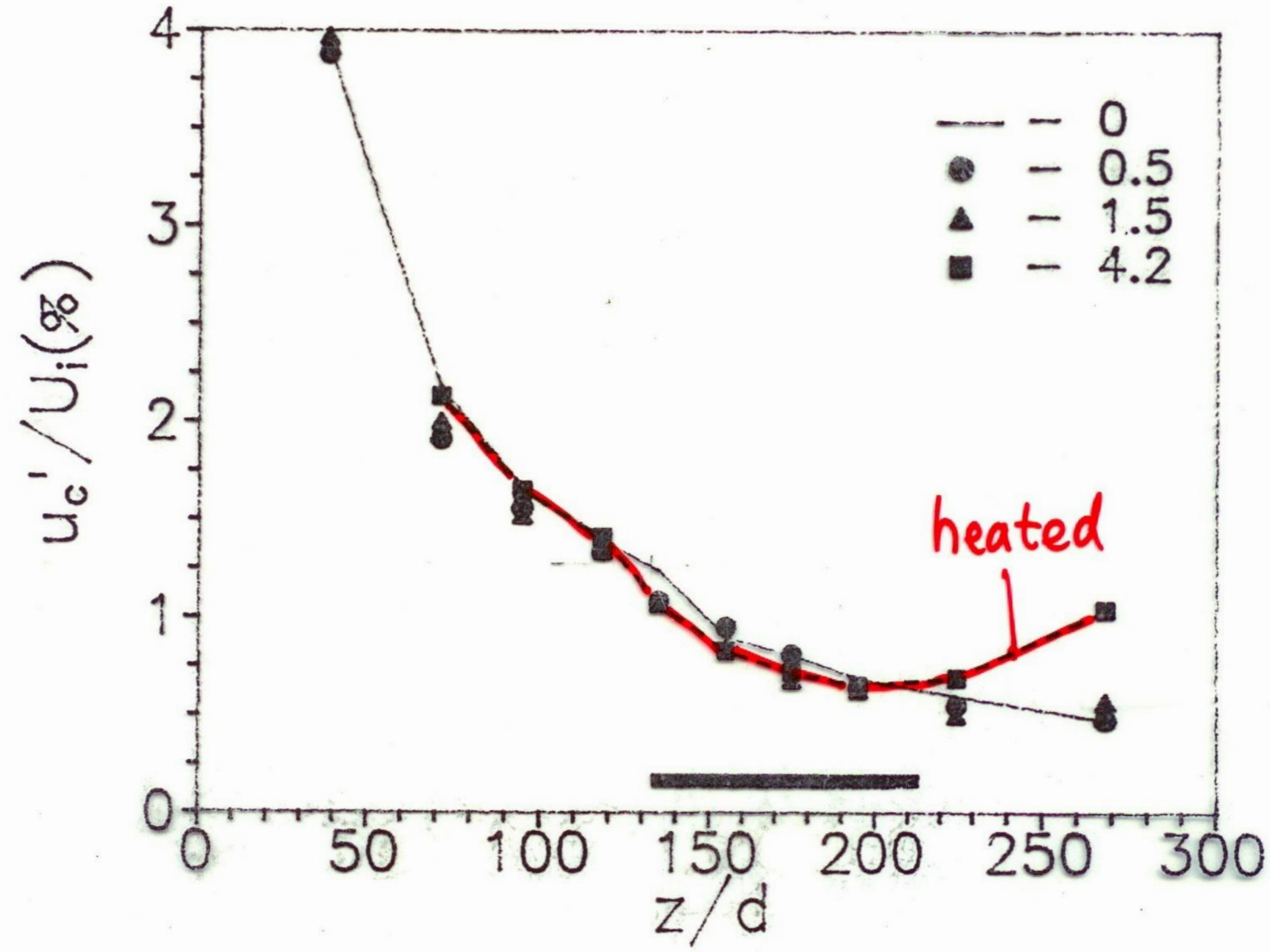
Stream-wise variation of scalar jet width at different values of the heating parameter Bhat, RN 1996, *JFM*

HEATING ACCELERATES FLOW



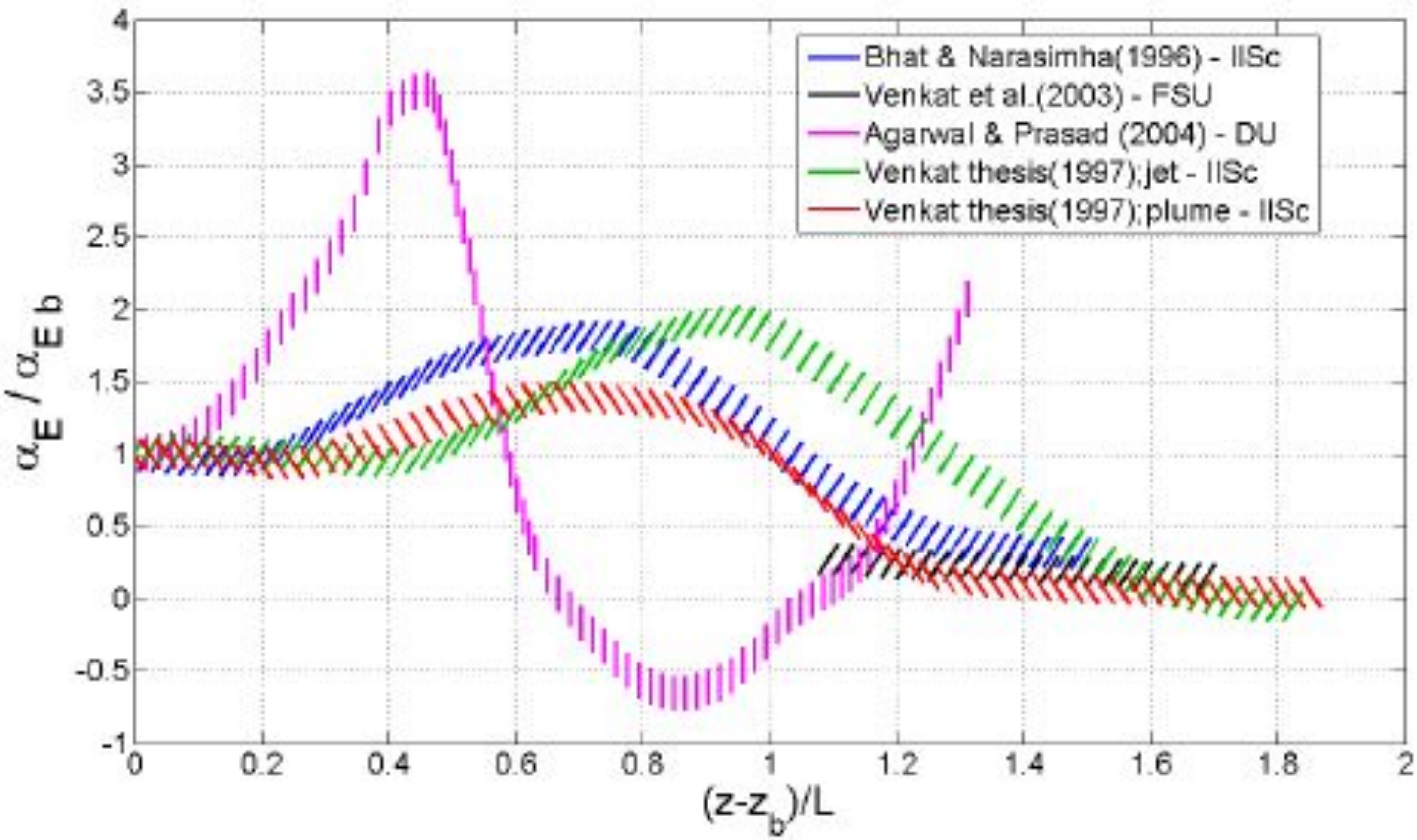
Variation of the axial component of the centreline velocity in the heated jet. Re_o =1480 and d = 8 mm Bhat, RN 1996, *JFM*

TURBULENCE IN CLOUD-FLOW



COMPARISON WITH REAL CLOUDS

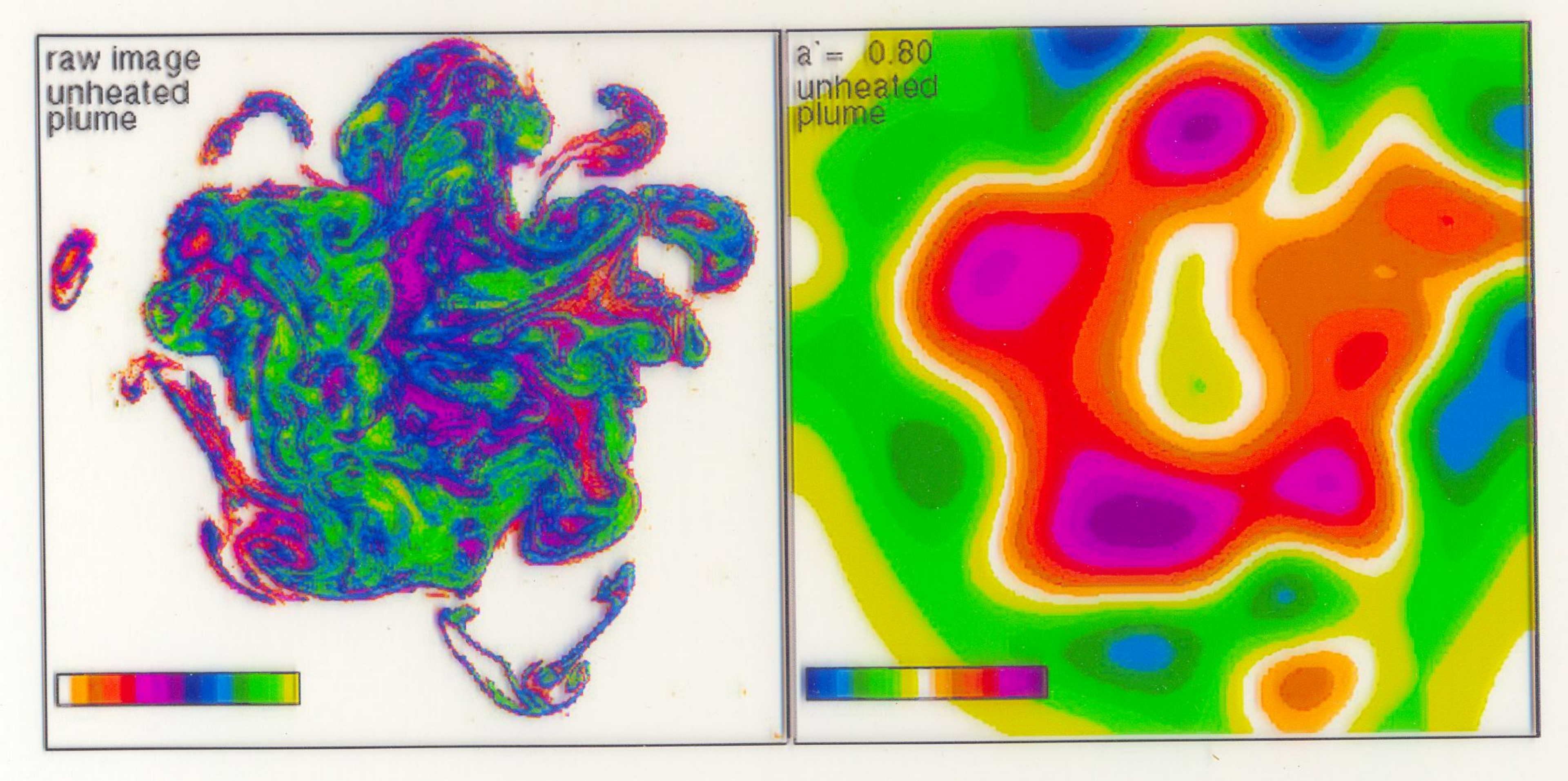
Entrainment Coefficient



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

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

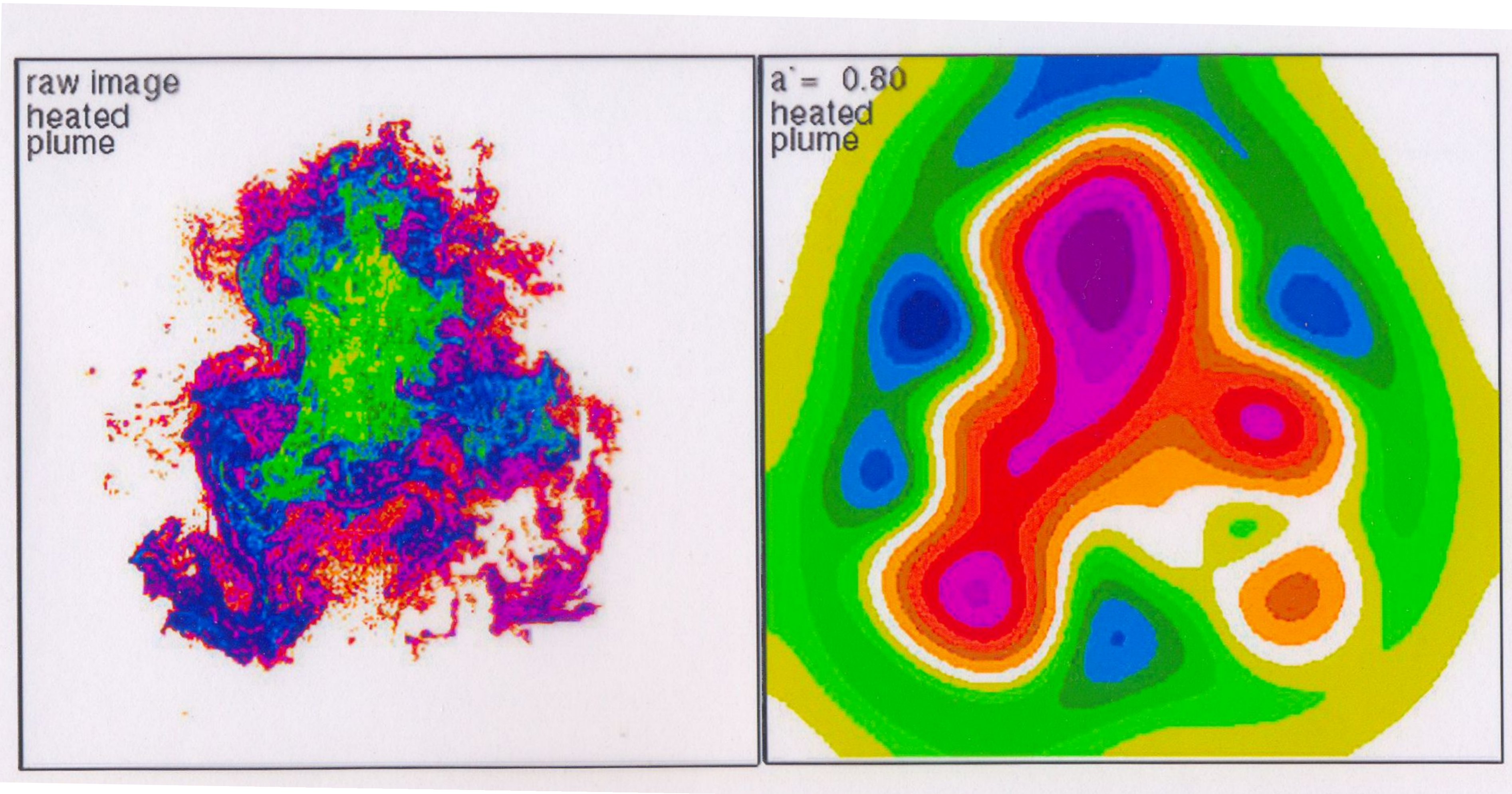
WAVELETS REVEAL HIDDEN ORDER, ORDINARY PLUME



Turbulent chaos conceals lobed vortex ring ?

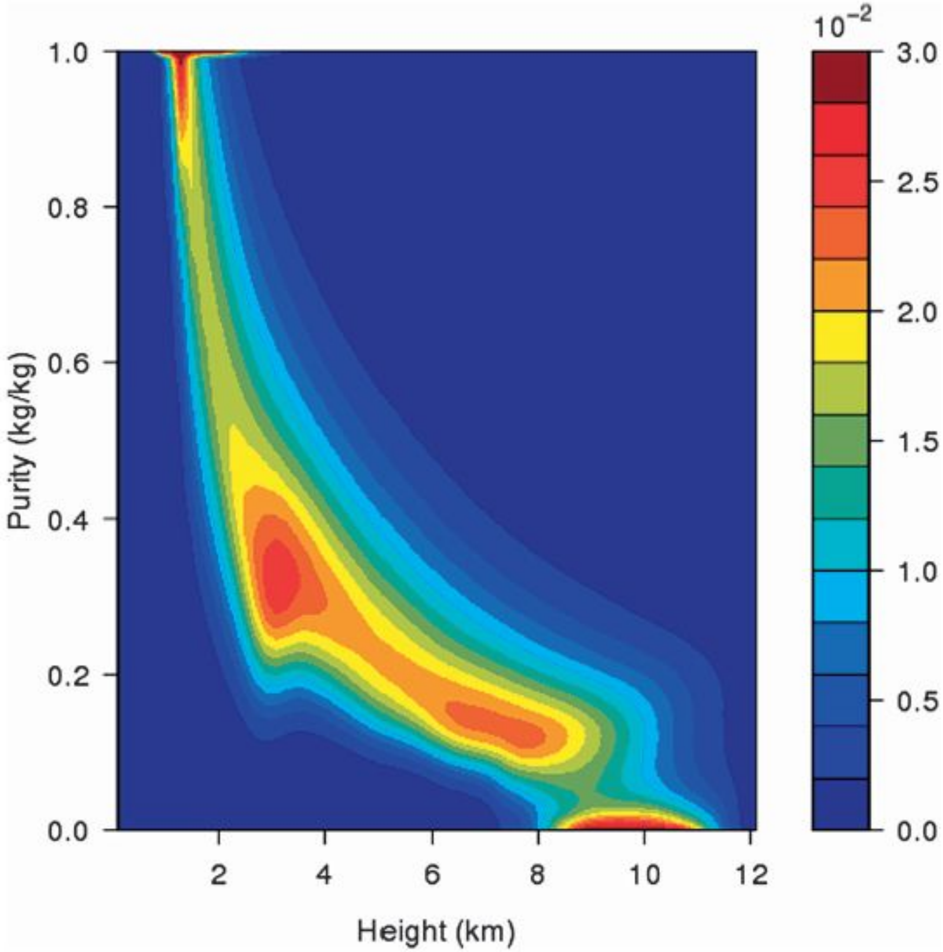
Narasimha et al. 2002 *Expts. Fl.*, Srinivas+ *2007* JoT

CLOUD PLUME: UNMIXED CORE

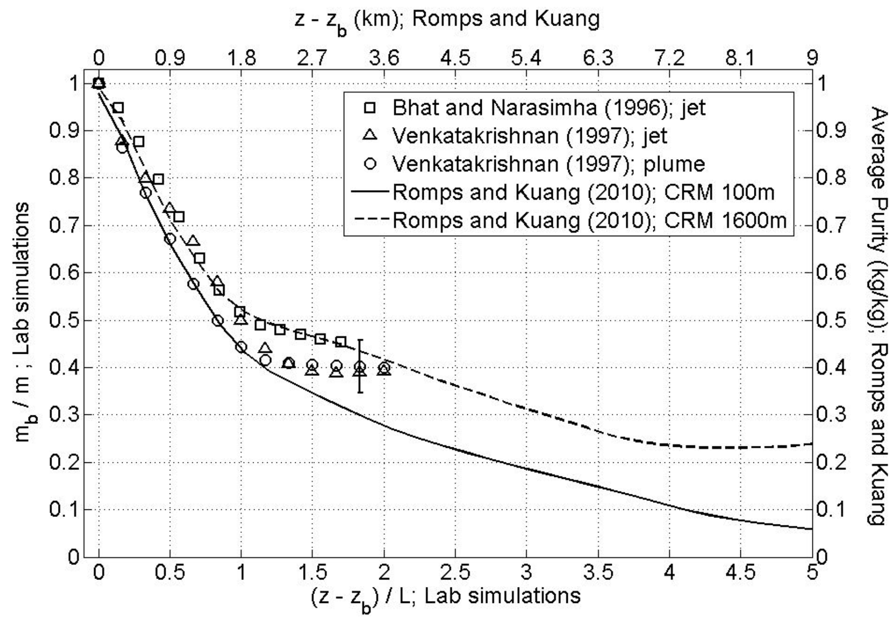


RN+ 2002 *Expts. Fl.*

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

T R A N S I E N T   D I A B A T I C   P L U M E

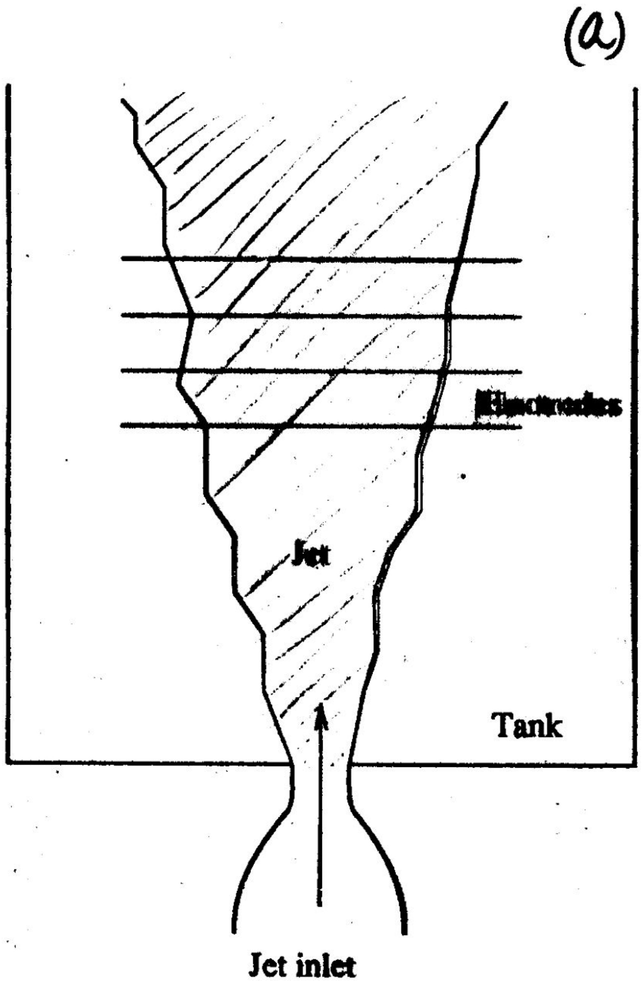
CYBER CLOUDS 1

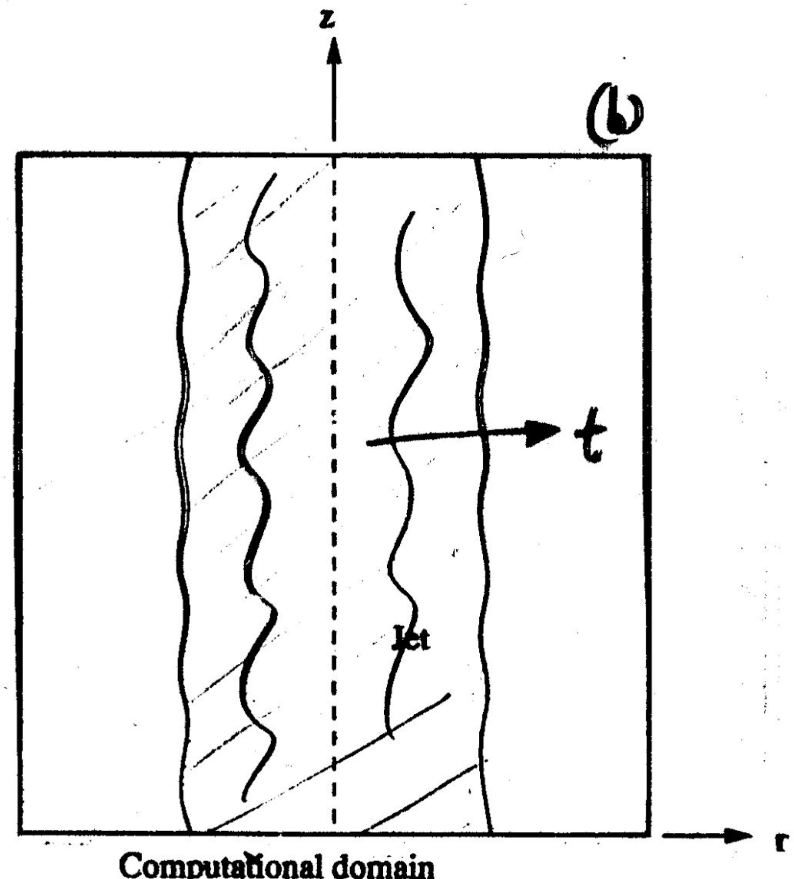
SPECTRAL METHODS

MEGHA 1

TRANSIENT DIABATIC JET

LABORATORY SETUP VERSUS TEMPORAL SIMULATION





Basu, Narasimha 1999, *JFM*

INITIAL AND BOUNDARY CONDITIONS

$$
\begin{aligned}
w &= 1, && \forall r \leqslant r_0 - \delta/2 \\
&= 0, && \forall r \geqslant r_0 + \delta/2 \\
&= \frac{1}{2}\left(1 - \tanh\frac{r - r_0}{2\theta_0}\right), && \forall r_0 - \delta/2 < r < r_0 + \delta/2,
\end{aligned} \qquad (2.9)
$$

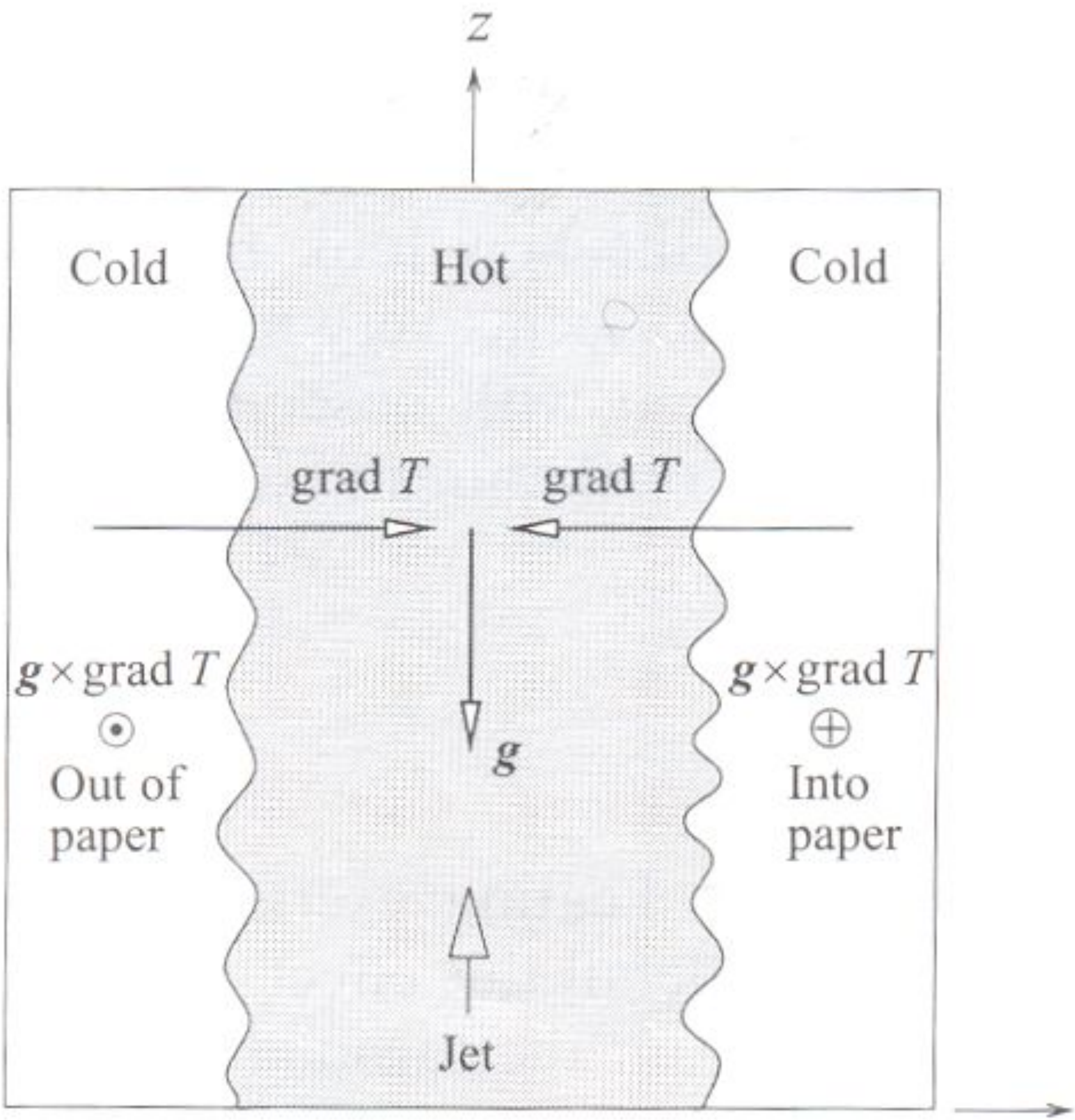
where δ is the characteristic width of the shear layer. Here r_0 is the initial mean radius of the shear layer, θ_0 is the initial momentum thickness, and u_θ and u_r are assumed to be zero everywhere. We impose a small perturbation on this shear layer corresponding to an increment in u_r given by

$$
\Delta u_r = f(r)\left[\sum_j a_j \sin\left(\frac{2\pi z}{\lambda_j} + \varphi_j\right) + a_\theta \sum_l \sin(l\theta + s_l)\right], \qquad (2.10)
$$

with prescribed amplitudes a_j and a_θ, streamwise wavelength λ_j and phases φ_j and s_l; $f(r)$ is the filtering function

$$
f(r) = \exp\left[-2\left(\frac{r - r_0}{\delta}\right)^2\right], \qquad (2.11)
$$

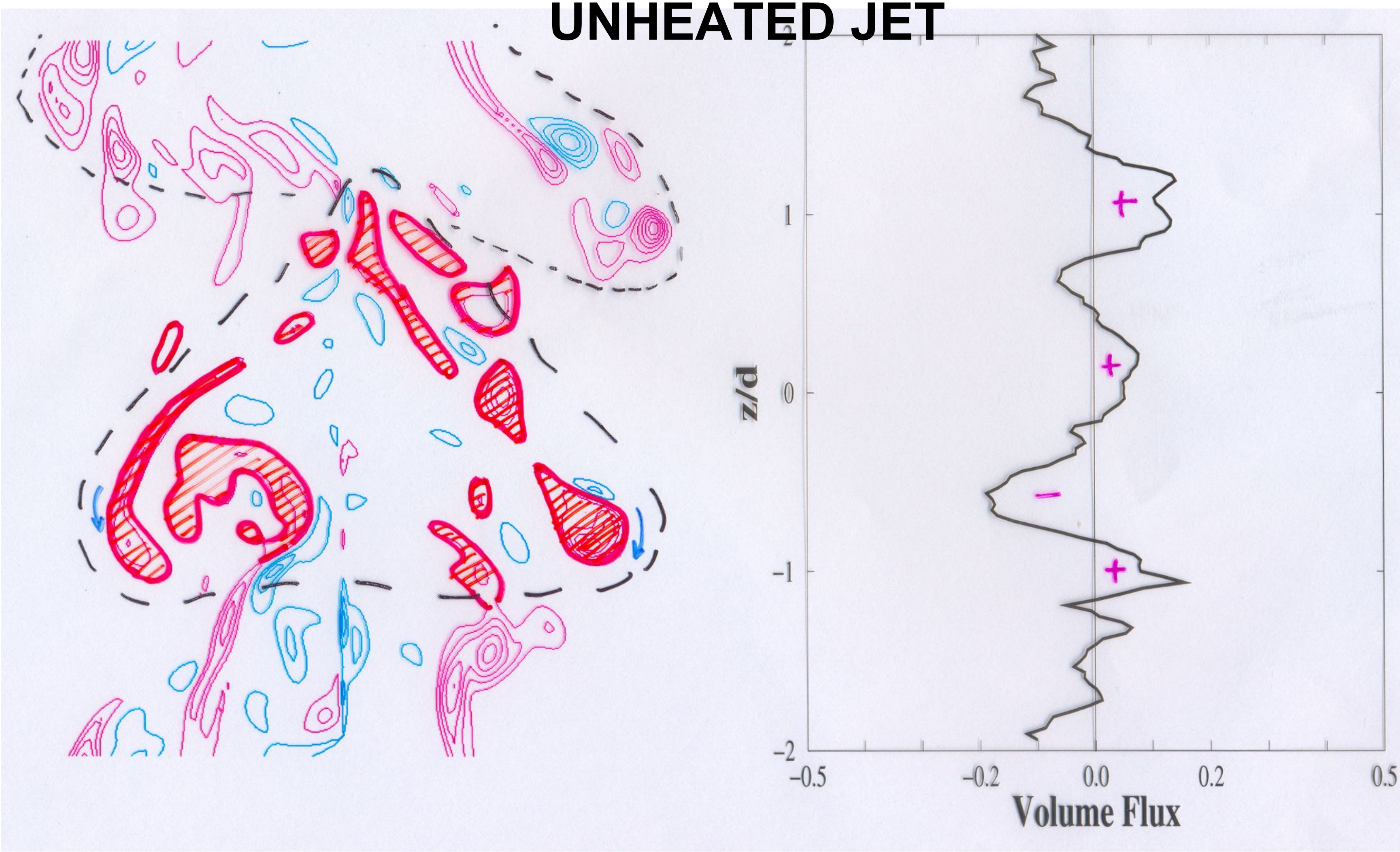
CREATING VORTICITY BY BAROCLINIC TORQUE



Basu, RN 1999 *J. Fluid Mech.*

COHRERENT STRUCTURE IN AZIMUTHAL VORTICITY

UNHEATED JET



t = 35, x = 65

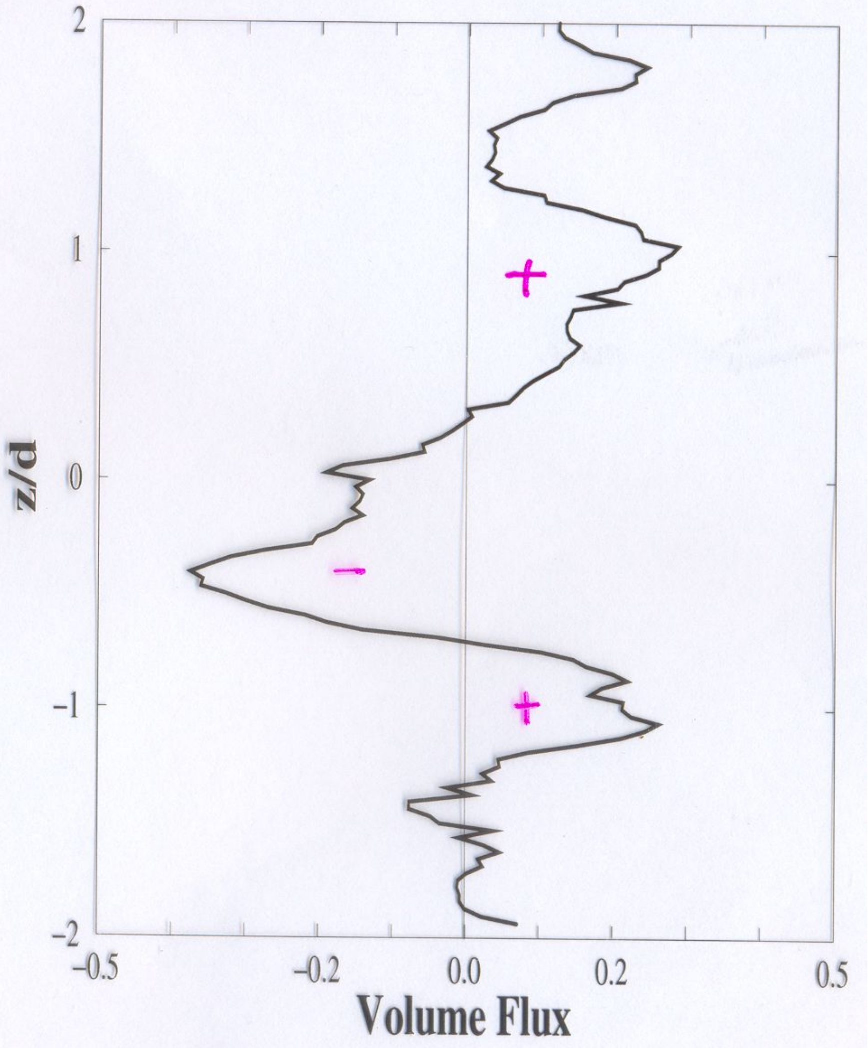
Volume flux vs. z/d at t = 35

RN, Shivakumar 1999 IUTAM Goettingen

AZIMUTHAL VORTICITY

FULLY HEATED JET

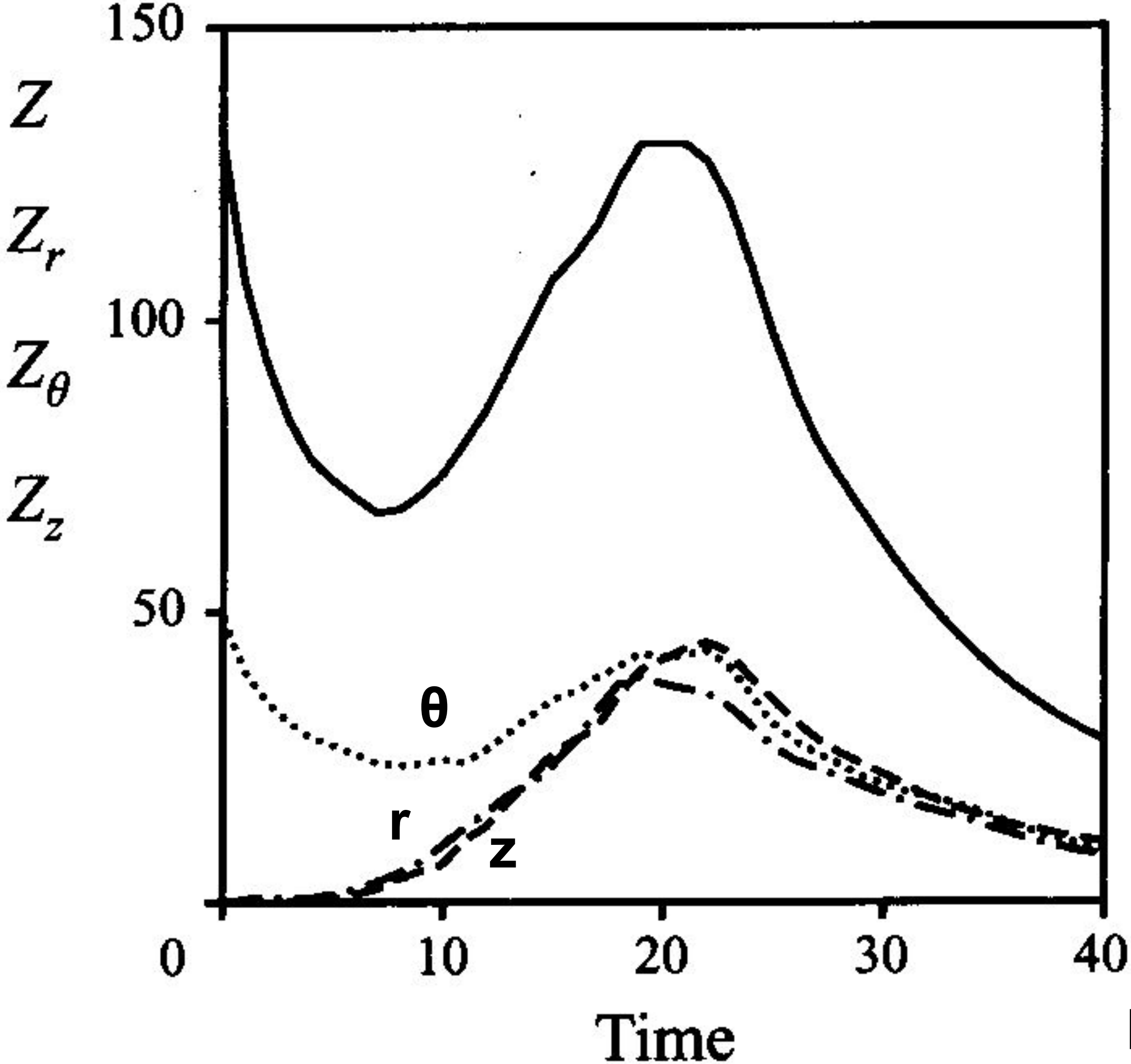
t = 35, x = 65



Volume flux vs. z/d at t = 35

RN, Shivakumar 1999 IUTAM Goettingen

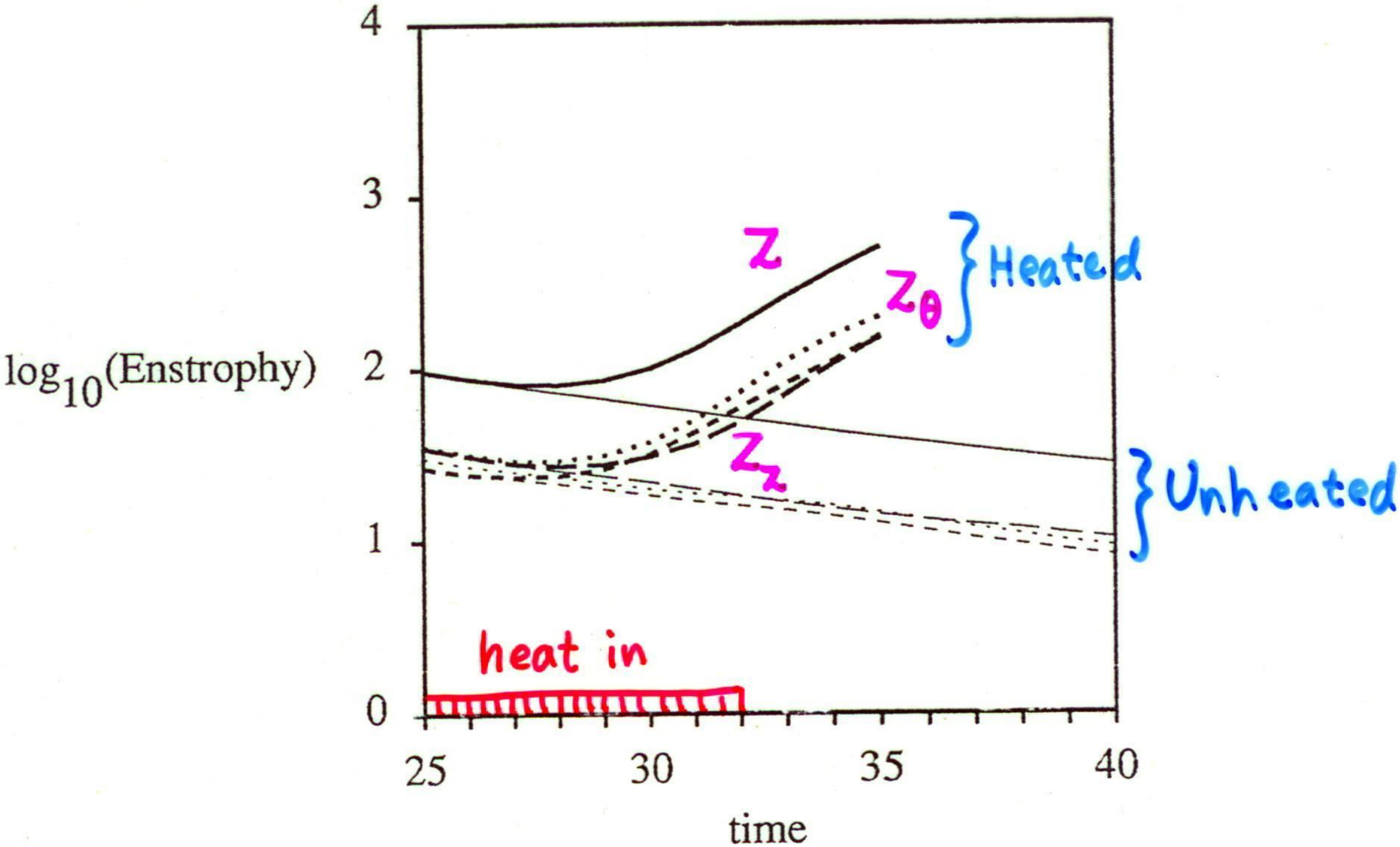
ENSTROPHY IN ORDINARY JET



Enstrophy = mean squared fluctuating vorticity

Basu, RN 1999 *JFM*

ENSTROPHY INCREASE WITH HEATING



Basu, RN 99, *JFM*

TRANSIENT DIABATIC PLUME

MEGHA 3

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 129×10^6.
- Poisson solver: Preconditioned (multi-grid based) GMRes.

SIMULATION STATISTICS - I

Grid size:129 M
Time step: 0.0025
Number of time steps: 26,000
Total hard disk, including post-processing at 4PI cluster: 5 TB
Size of code: A few hundred KB / 5000 lines
Simulation run on: 216 CPUs
Compute time: 0.12 M core hours (~6 days wall time)

Prasanth 2013 MS thesis, JNC

SIMULATION STATISTICS - II

Final simulation (November 2013):

Grid size: 2.5 B
Time step: 0.00125
No. of time steps : 52,000
Total hard disk storage, including post-processing at 4 PI new cluster: 100 to 200 TB
Compute time: 8 M core hours (~ 15 to 20 days wall time) with 5320 CPUs

BASIC SCALES, NON-DIMENSIONAL NUMBERS

$$\mathrm{Re} = \frac{U_o d_o}{\nu}$$ → Reynolds Number

$$\mathrm{Pr} = \frac{\nu}{k}$$ → Prandtl Number

$$\mathrm{G} = \frac{J}{\rho c_p} \frac{d_o}{U_o T_o}$$ → Heat Release Number

$U_0 = \sqrt{g \alpha d_o T_o}$, d_0 = diameter of hot patch

T_0 = temperature differential of hot patch over ambient

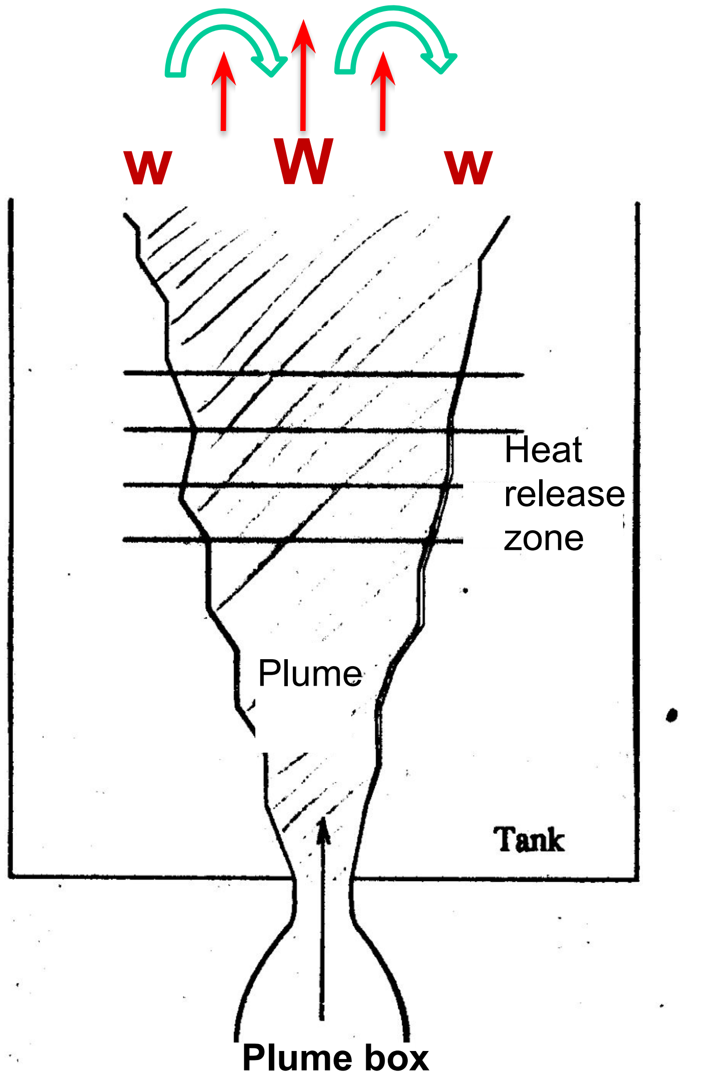
Results and Discussion

COMPARISON OF CLOUD SHAPES

Real **Cyber**


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


HOW THE BAROCLINIC TORQUE WORKS



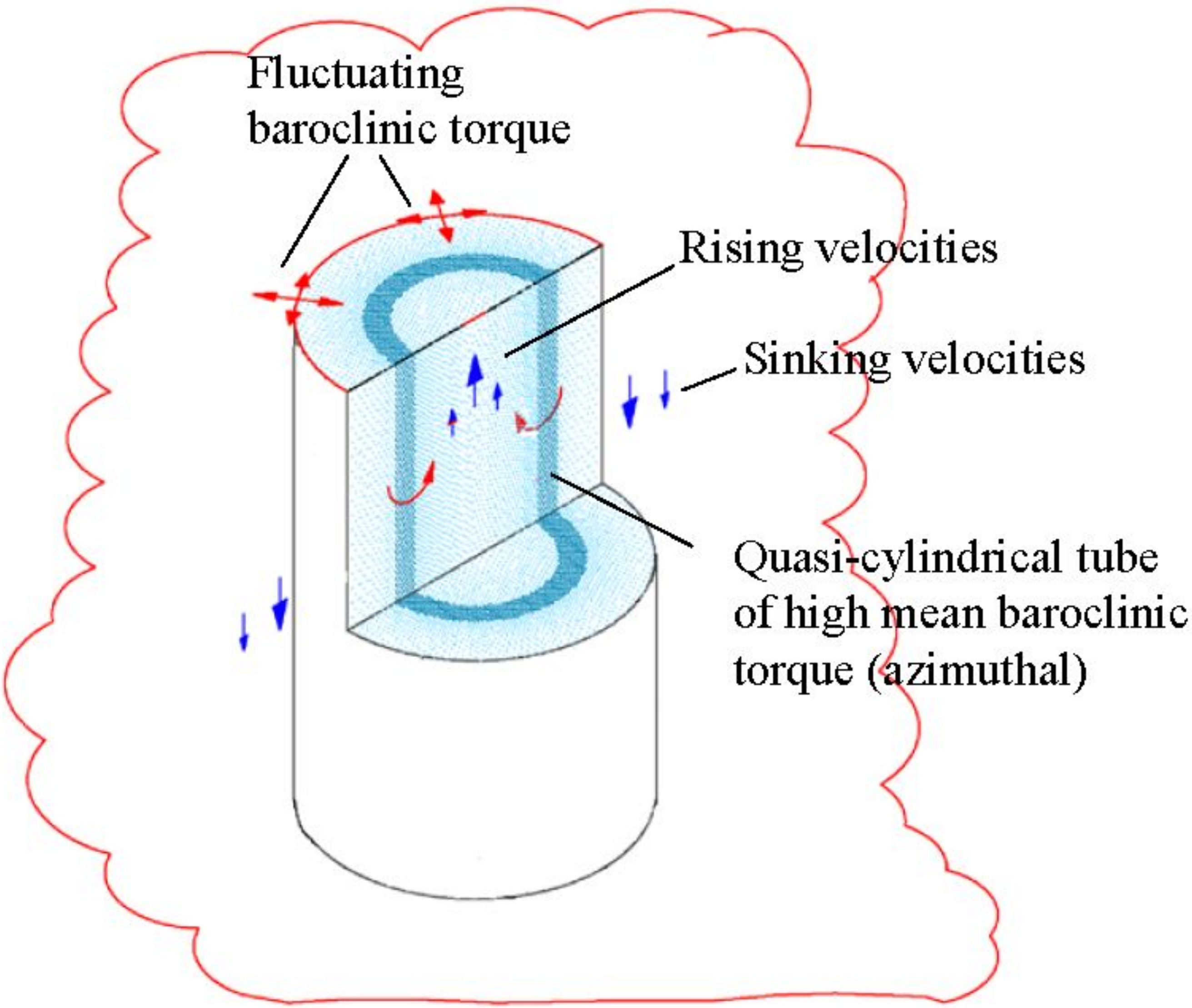
The Baroclinic Torque
The varying buoyancy force
Temperature gradient

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 ?

HOW THE BAROCLINIC TORQUE WORKS



VORTICITY BUDGET

- For simplicity, consider a temporal diabatic jet/plume (Basu, RN 1999)
- <u>Notation:</u>

	Mean	Fluctuations	Rms
Velocity	***U***	***u'***	
Vorticity	***Ω***	***ω'***	
Temperature		T'	
Strain rate	S_{ij}	s'_{ij}	

Vorticity budget continued…..

- <u>Navier-Stokes + Mean Vorticity</u>

$$\frac{\partial \Omega_i}{\partial t} = -\overline{u'_j \frac{\partial \omega'_i}{\partial x_j}}$$ {turbulent transport of turbulent vorticity}

$$+ \Omega_j S_{ij}$$ {mean flow stretching mean vorticity}

$$+ \overline{\omega'_j s'_{ij}}$$ {turbulent flow stretching turbulent vorticity}

$$+ \nu \frac{\partial}{\partial x_j} \frac{\partial \Omega_i}{\partial x_j}$$ {viscous diffusion} ---------------> (1)

RN 2012 *JoT*

Vorticity budget continued…..

- Turbulent enstrophy:

$$\frac{\partial}{\partial t}\left(\frac{\hat{\omega}^2}{2}\right) = -\overline{u'_j\omega'_i}\frac{\partial\Omega_i}{\partial x_j}$$ {generation by mean vorticity gradient}

$$+\frac{\partial}{\partial x_j}\left(\frac{\overline{\boldsymbol{\omega}'^2 u'_j}}{2}\right)$$ {turbulent transport}

$$+\ \overline{\omega'_i\omega'_j S_{ij}}$$ {stretching by mean strain}

$$+\ \overline{\omega'_i\omega'_j s_{ij}}$$ {stretching by turbulent strain}---★

$$+\ \nu\frac{\partial}{\partial x_j}\frac{\partial}{\partial x_j}\left(\frac{\hat{\omega}^2}{2}\right)$$ {viscous diffusion}

$$-\ \overline{\nu\left(\frac{\partial\omega_i}{\partial x_j}\frac{\partial\omega_i}{\partial x_j}\right)}$$ {viscous dissipation} ----------------★→(2)

Vorticity budget continued…..

- Noting: $\Omega \sim S \sim \frac{U_c}{b}$, $\widehat{\omega} \sim s \sim \frac{\widehat{u}}{\lambda} \sim \Omega\, Re^{\frac{1}{2}}$, $\hat{u} \sim U_c$, $\mathrm{Re} = \frac{U_c b}{\nu}$,

  introducing Kolmogorov: $l_k = (\frac{\nu^3}{\varepsilon})^{\frac{1}{4}}$, $u_k \sim \frac{\nu}{k}$ and taking

  $\frac{\partial \omega_i}{\partial x_j} \sim \frac{\widehat{u}'}{\lambda} \cdot \frac{1}{l_k}$,

  we have enstrophy dissipation $\sim \nu \frac{\widehat{u}^3}{\lambda^3}$.

  Only the starred terms survive! So, with heating

$$\frac{\partial}{\partial t}(\frac{\widehat{\omega}^2}{2}) = \overline{\omega'_i \omega'_j s_{ij}} - \nu\overline{(\frac{\partial \omega_i}{\partial x_j}\frac{\partial \omega_i}{\partial x_j})} + (\beta \boldsymbol{g}.(\overline{\boldsymbol{\omega}' \mathrm{x} (\nabla \mathrm{T}')}))$$ ---------> (3)

THE VORTICITY SOURCE

The source for enstrophy is

$$\overline{\beta \boldsymbol{\omega}' . (\mathbf{g} \times \nabla T')} \equiv \beta \mathbf{g} . (\overline{\boldsymbol{\omega}' \times \nabla T'}). \tag{10}$$

Noting that $\beta \nabla T' = -(\nabla \rho')/\rho_o$, and taking $\nabla \rho'$ as of order $\hat{\rho}_c/\lambda_\rho$, where $\hat{\rho}_c$ is (say) the centreline rms of value ρ', and introducing λ_ρ as the Taylor microscale for the density field (although no measurements of λ_ρ are known to the author), the enstrophy source is of order

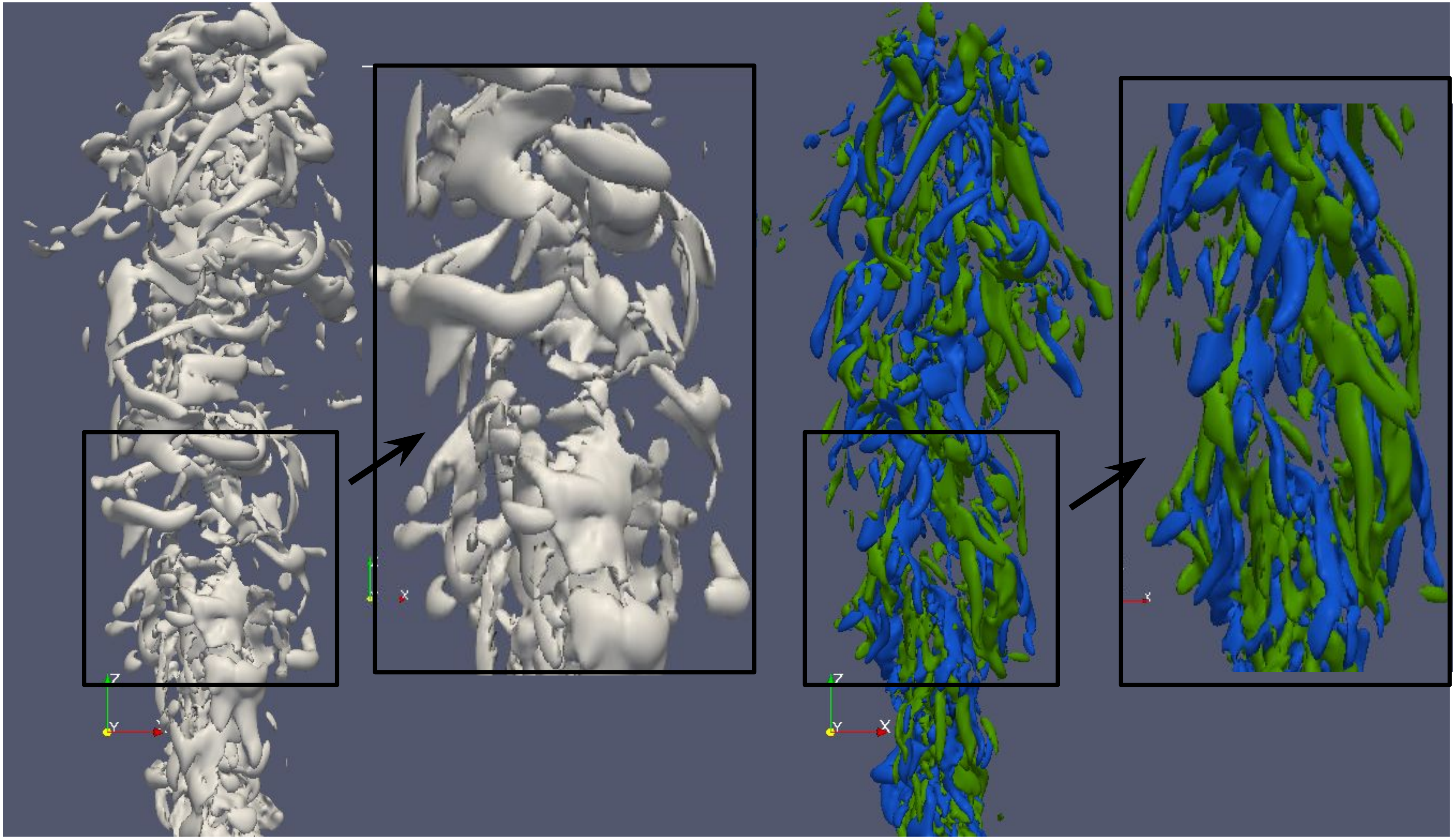
$$\frac{\mathbf{g}}{\rho_o} \frac{U_c}{\lambda} \frac{\hat{\rho}_c}{\lambda_\rho}, \tag{11}$$

where $\hat{\rho}$ will be determined by the heat release. This term seems to be responsible for the explosive increase in enstrophy found in the BaN simulations, particularly in the spectrum at high wave numbers (see Figure 5f).

Vorticity iso surface for plumes

Azimuthal component (-1.0)

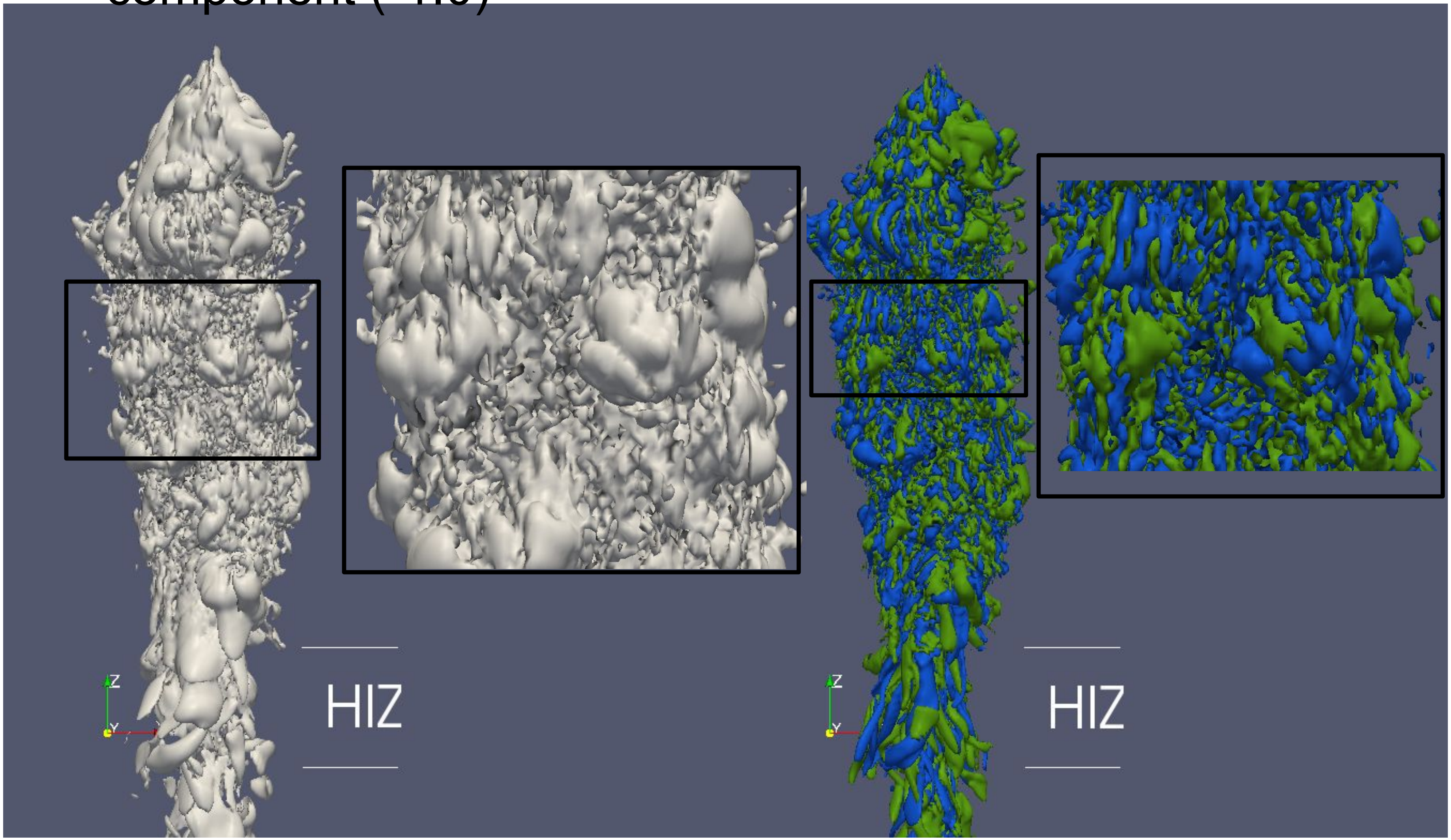
Axial component (-1.0 blue, +1 green)



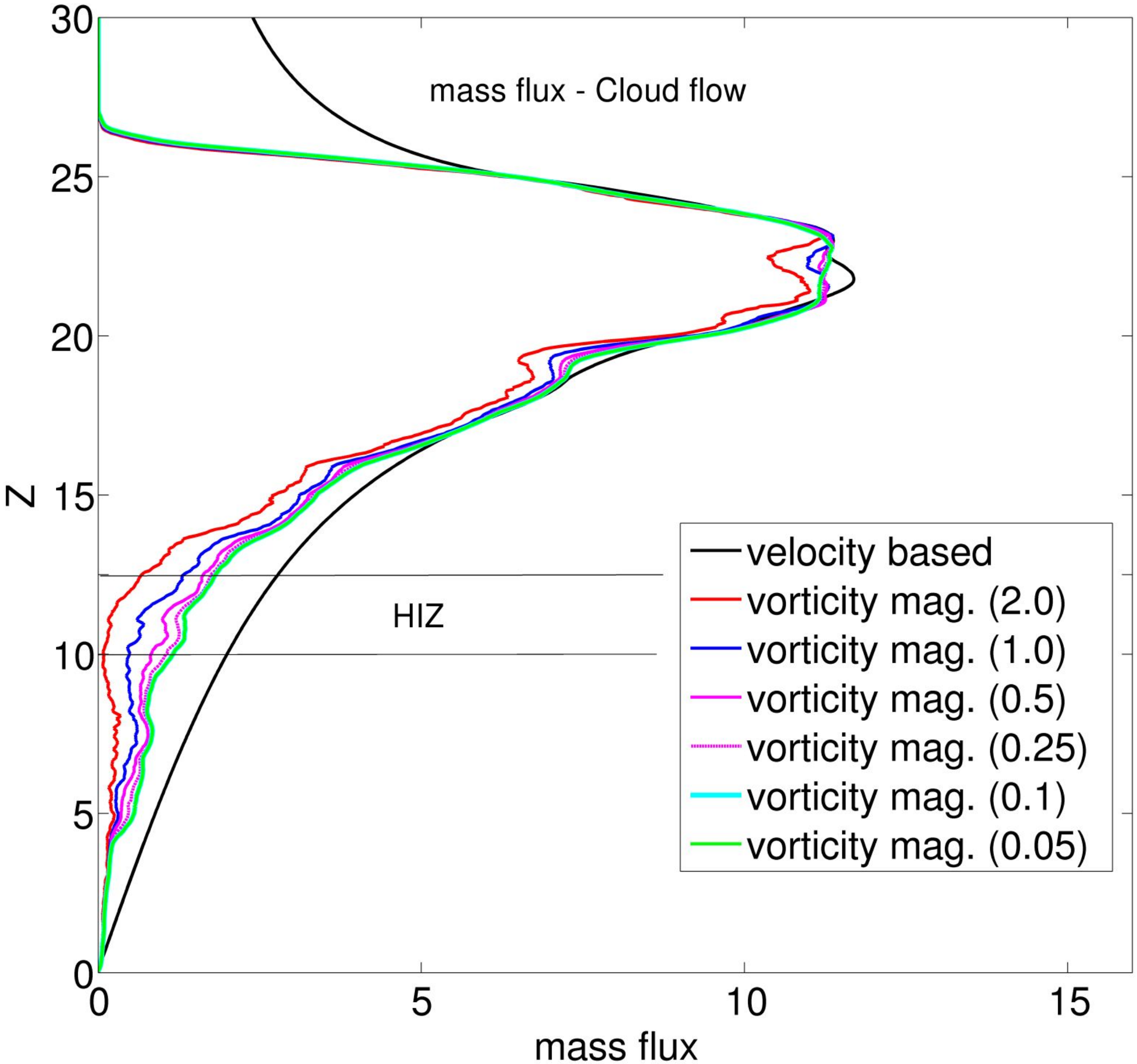
Vorticity iso surface for cloud flow

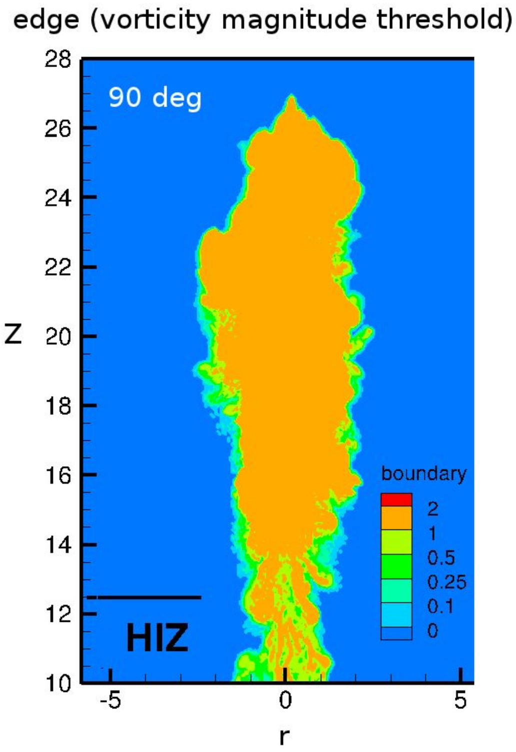
Azimuthal component (-1.0)

Axial component (-1.0 blue, 1.0 green)

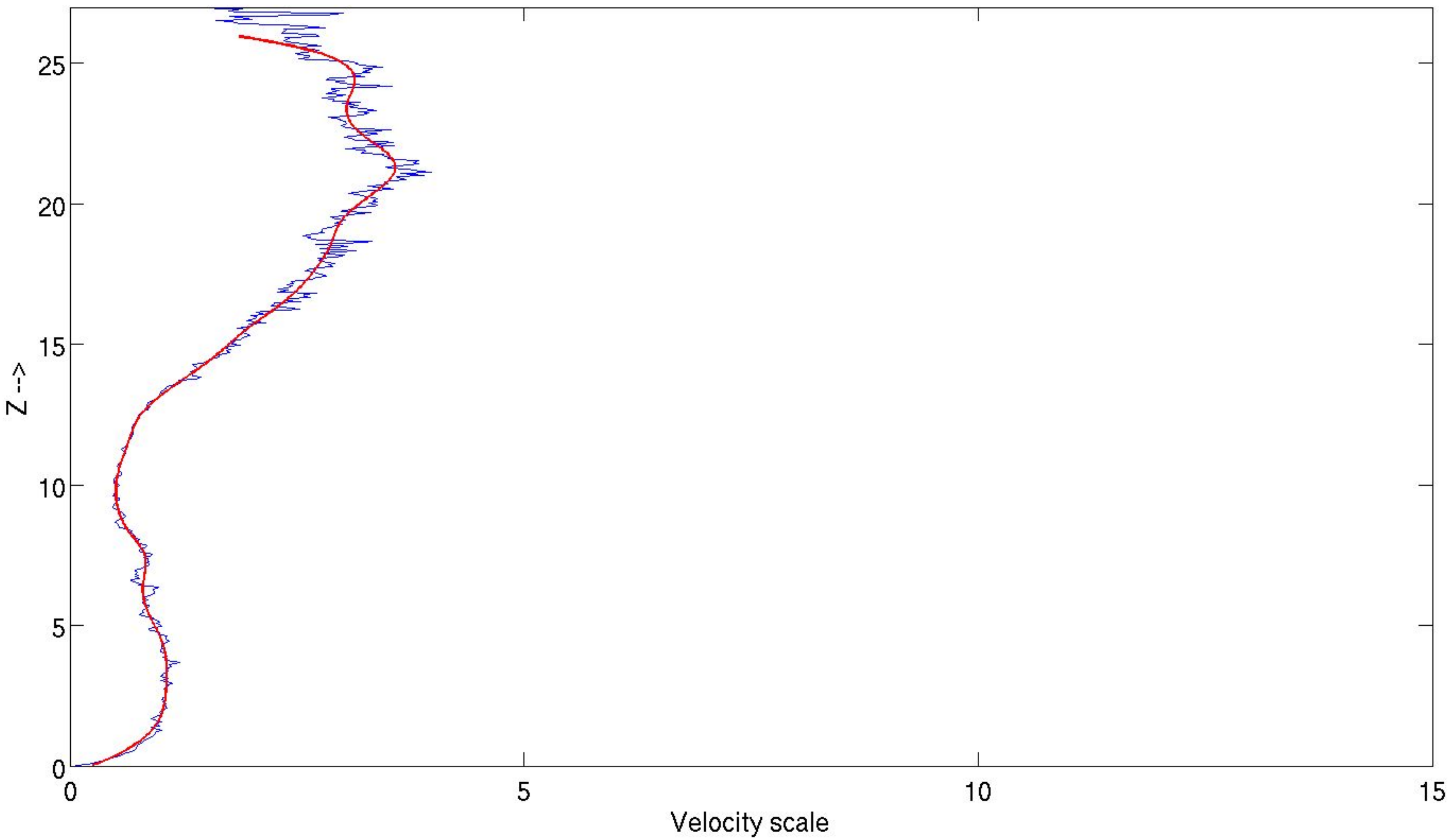


WHAT IN-CLOUD MASS FLUX ?

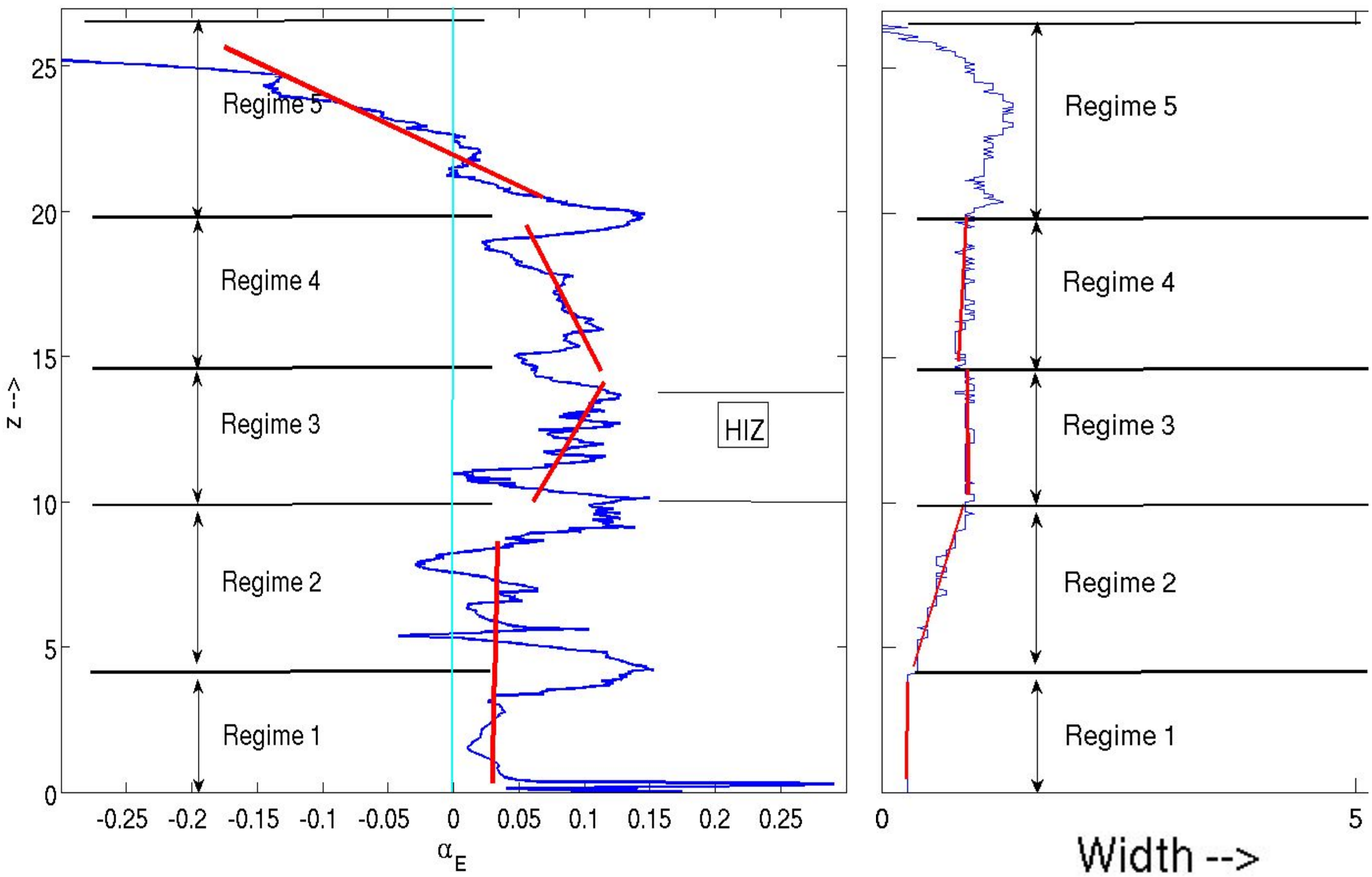




Velocity scale



Entrainment coefficient and width



HEATED PLUME

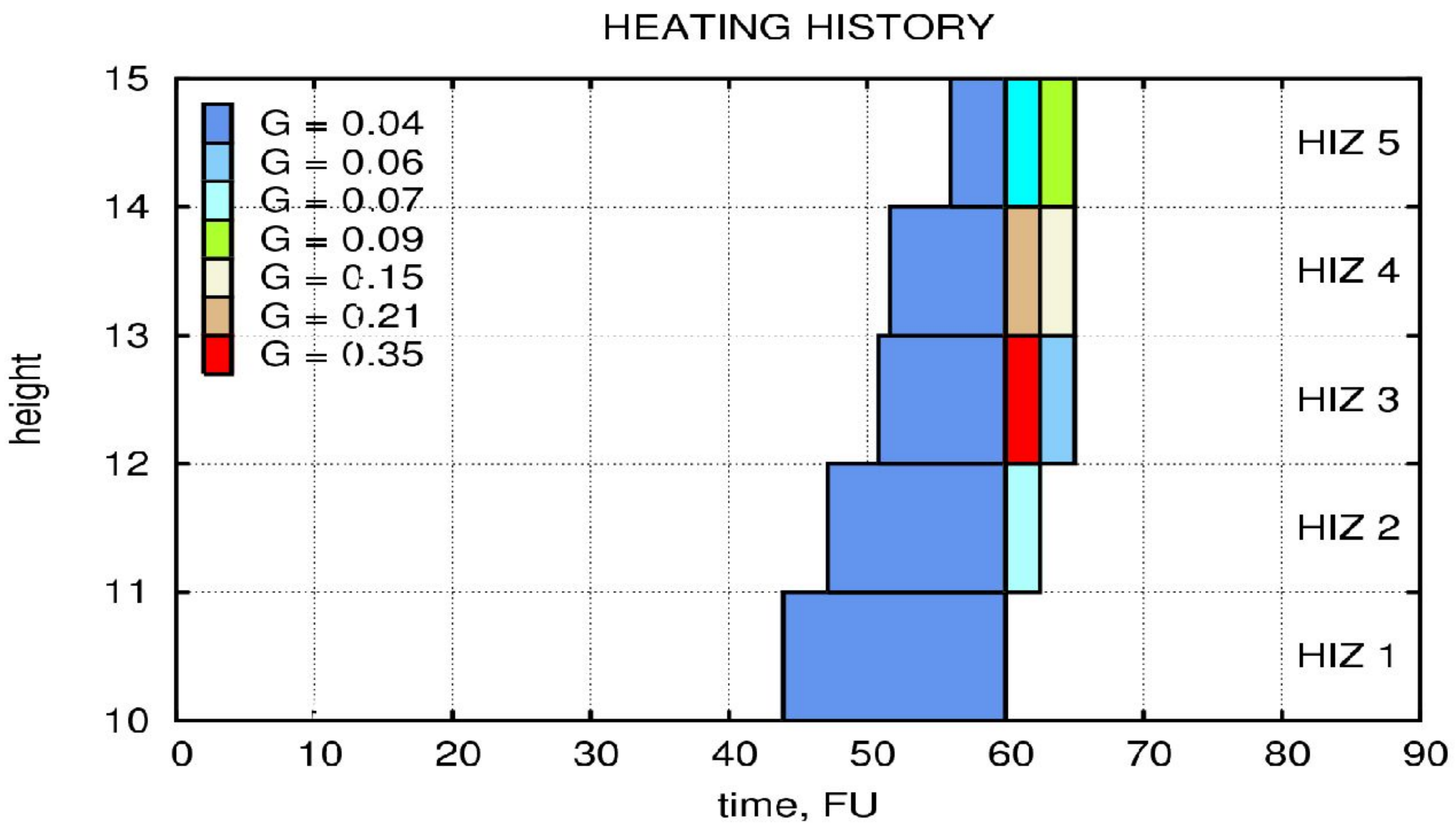
Re = 2000

Totally 90 FU

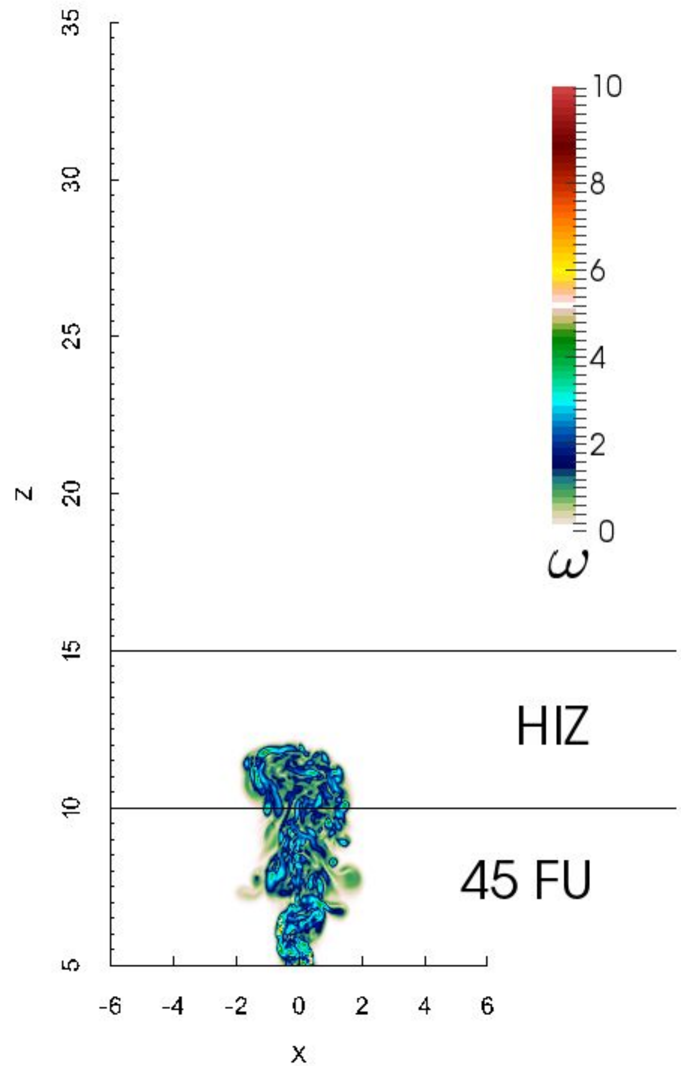
HIZ : 10 – 15 diameters

Heating stops at 65 FU

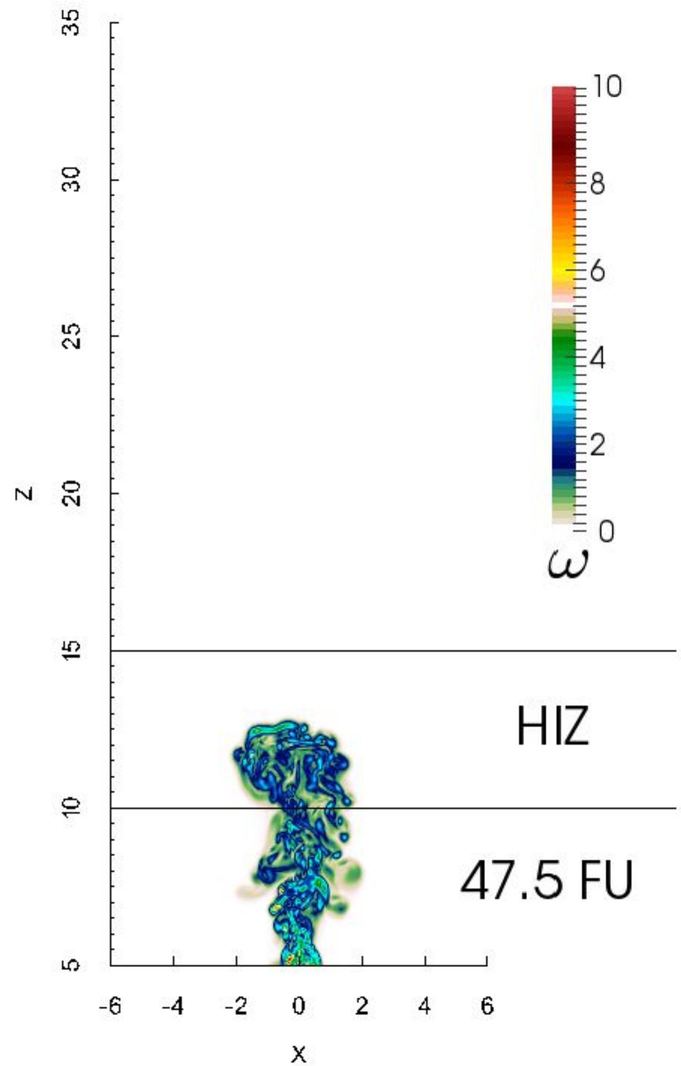
Axial sections at y = 0



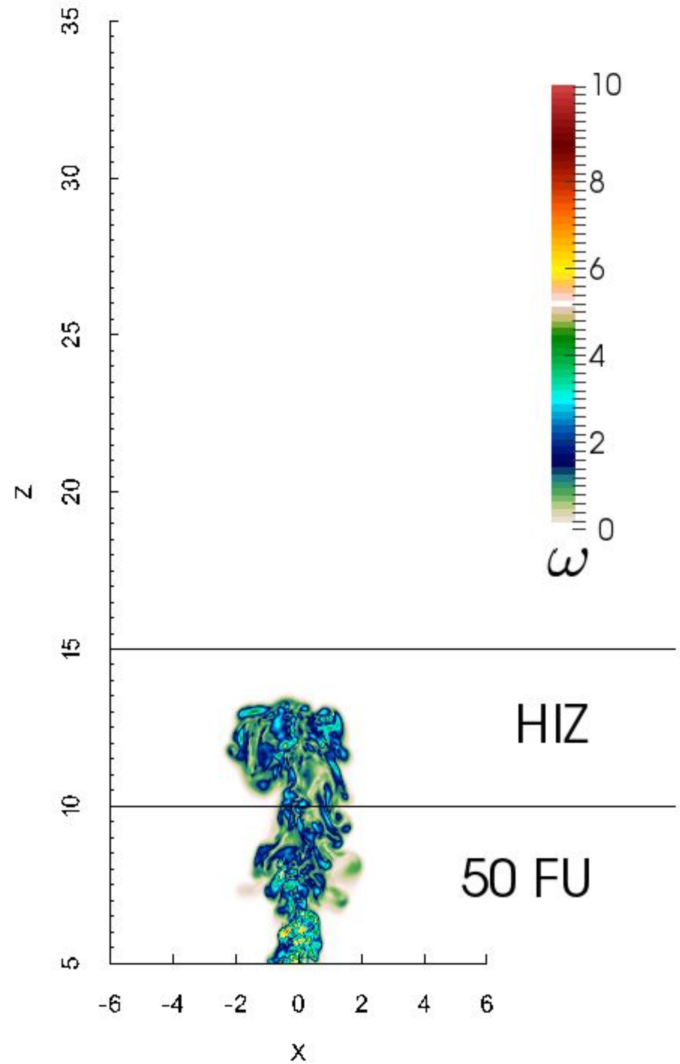
HEATING HISTORY
G = 0.04
G = 0.06
G = 0.07
G = 0.09
G = 0.15
G = 0.21
G = 0.35
HIZ 5
HIZ 4
HIZ 3
HIZ 2
HIZ 1
height
15
14
13
12
11
10
0
10
20
30
40
50
60
70
80
90
time, FU



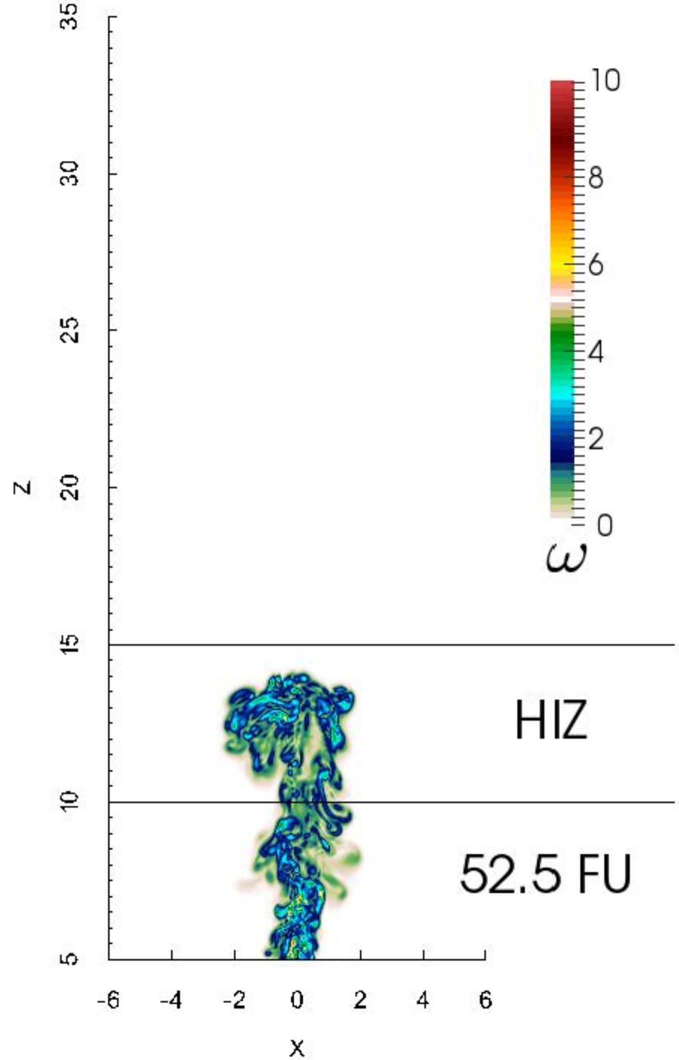
Z
X
HIZ
45 FU
ω

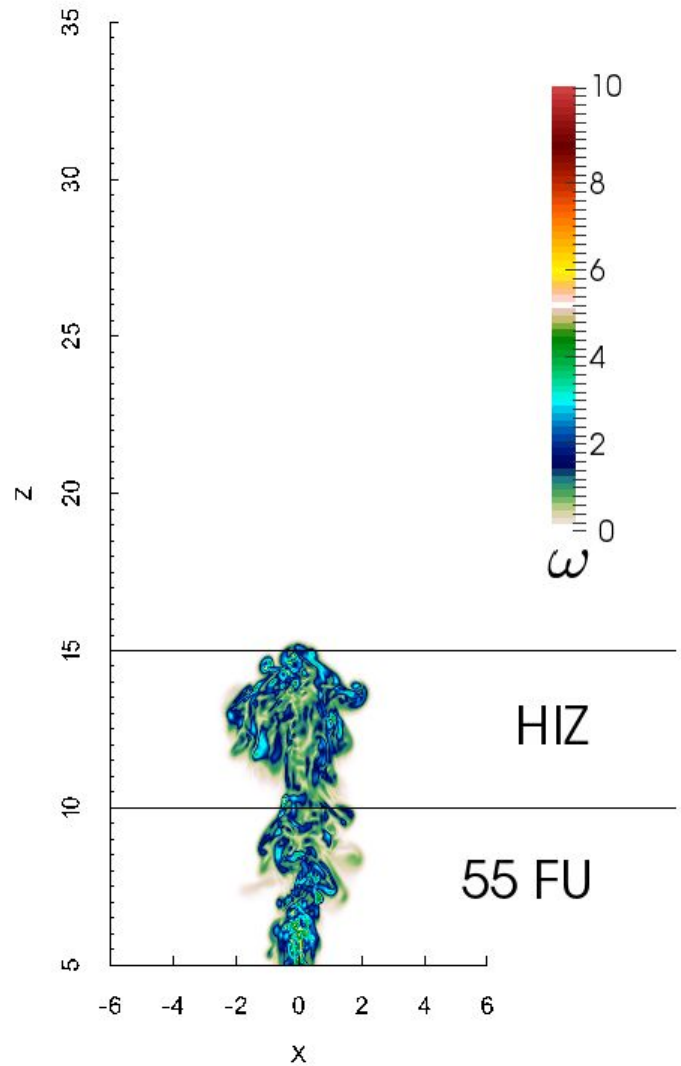


Z
X
HIZ
47.5 FU
ω

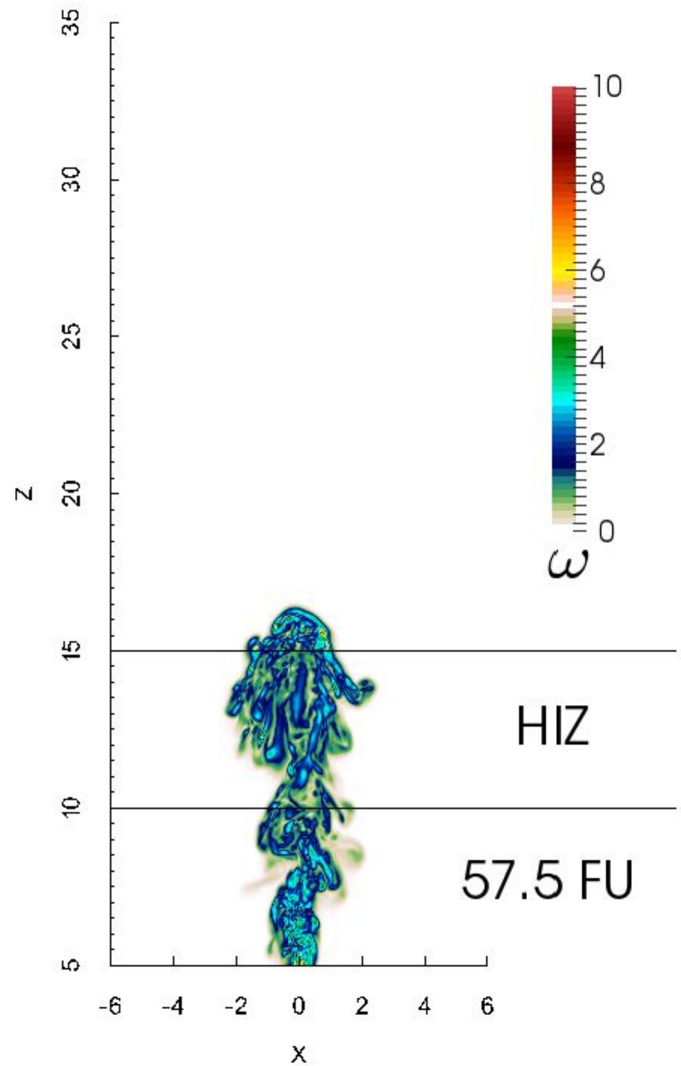


HIZ
50 FU
Z
X
ω

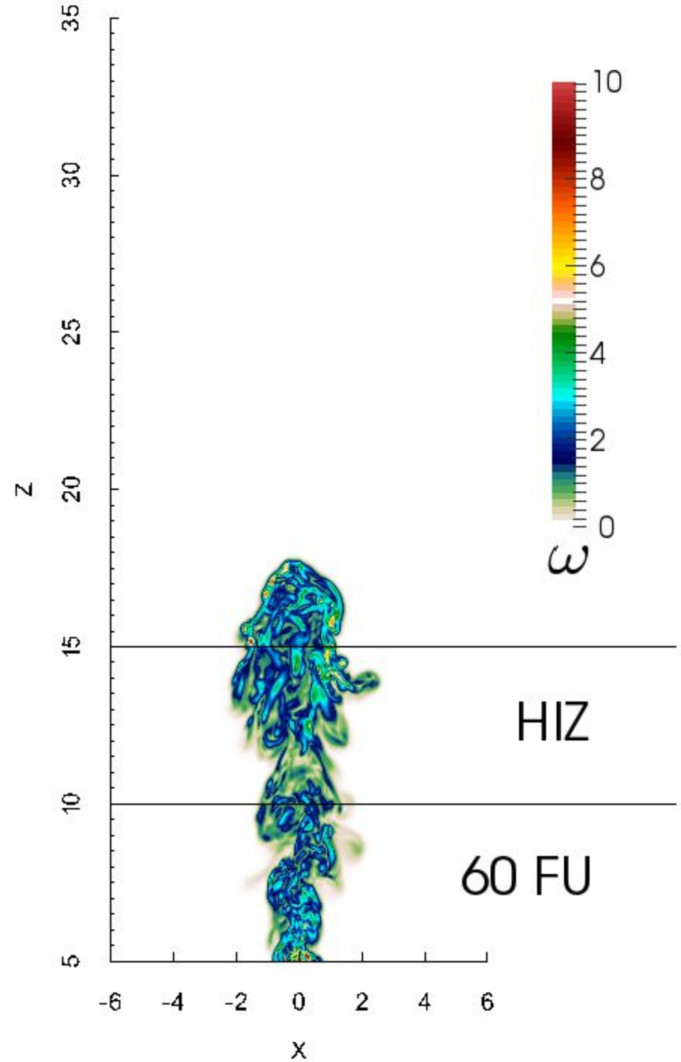

35
30
25
20
15
10
5
Z
-6
-4
-2
0
2
4
6
X
10
8
6
4
2
0
ω
HIZ
52.5 FU



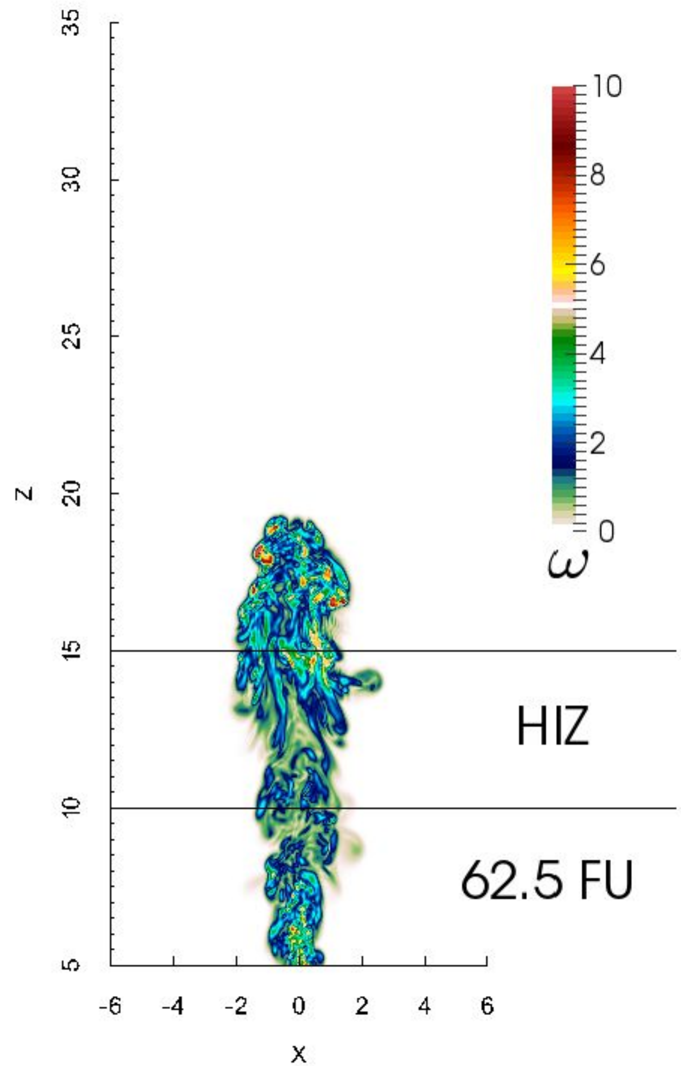
35
30
25
20
15
10
5
Z
10
8
6
4
2
0
ω
HIZ
55 FU
-6
-4
-2
0
2
4
6
X



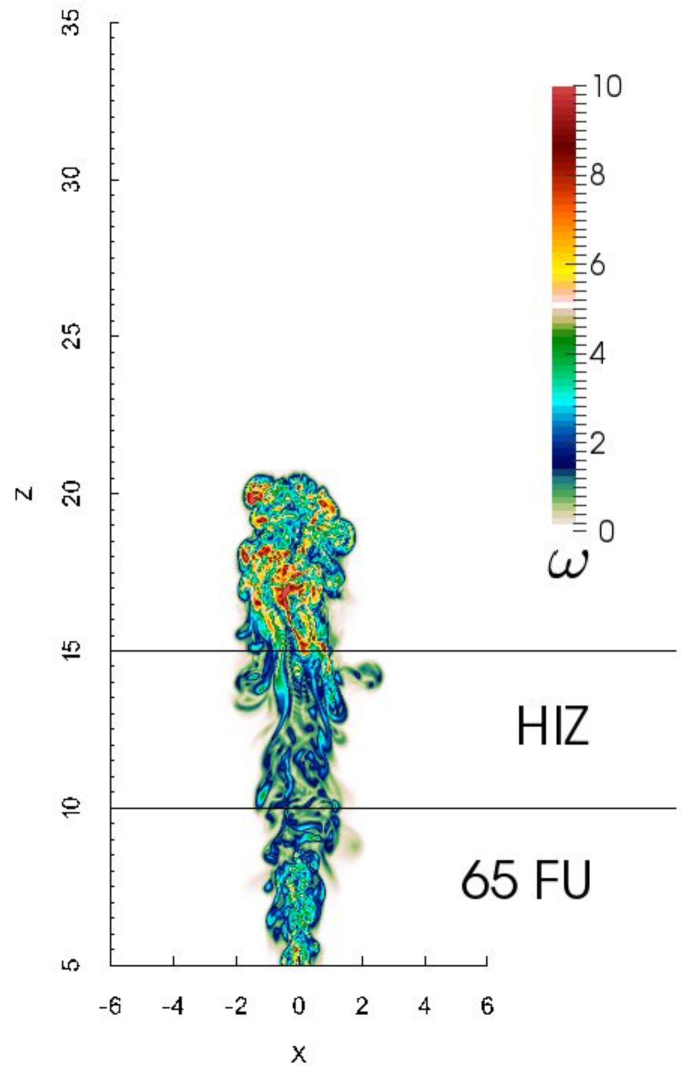
10
8
6
4
2
0
ω
HIZ
57.5 FU
35
30
25
20
15
10
5
Z
-6
-4
-2
0
2
4
6
X



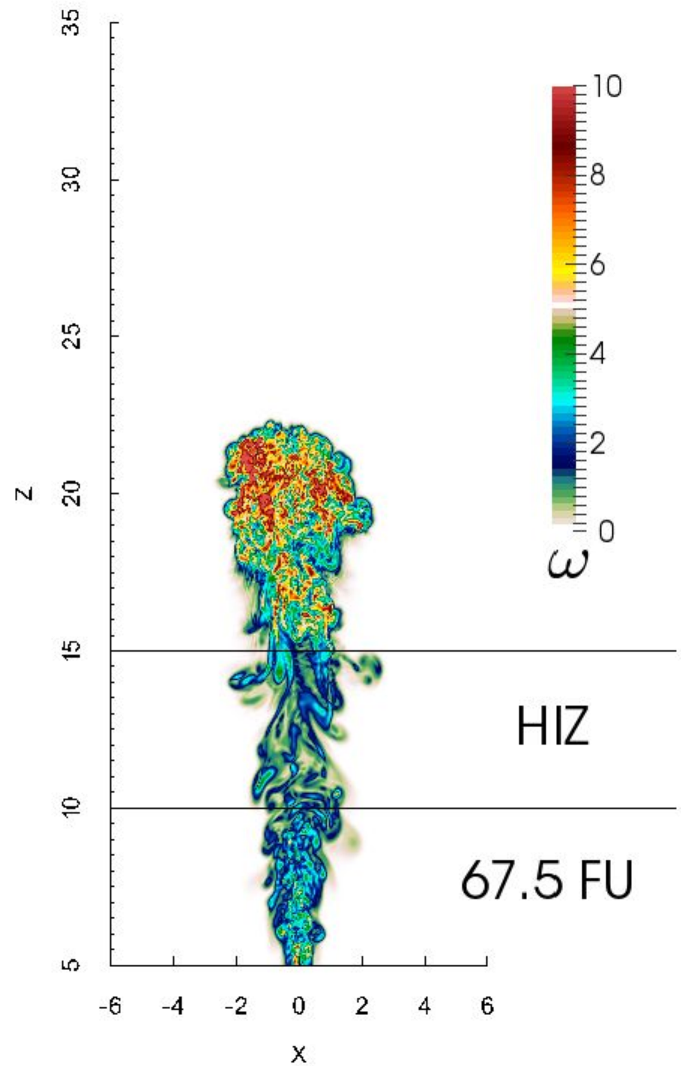
z
x
ω
HIZ
60 FU



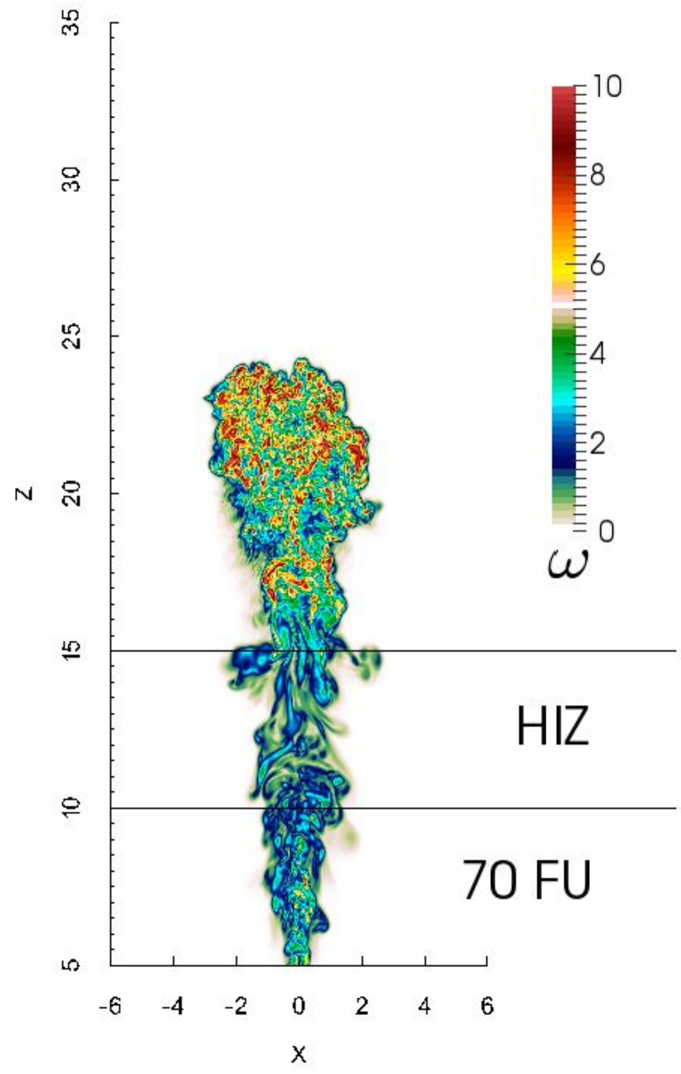
HIZ
62.5 FU
z
x
ω



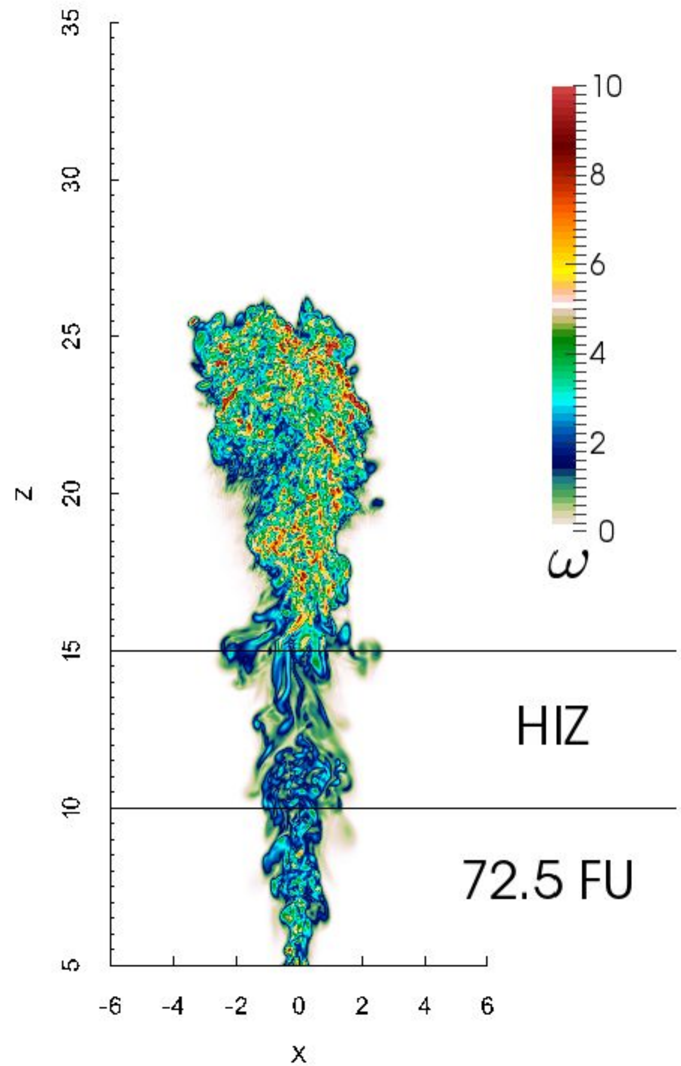
35
30
25
20
15
10
5
z
-6 -4 -2 0 2 4 6
x
10
8
6
4
2
0
ω
HIZ
65 FU



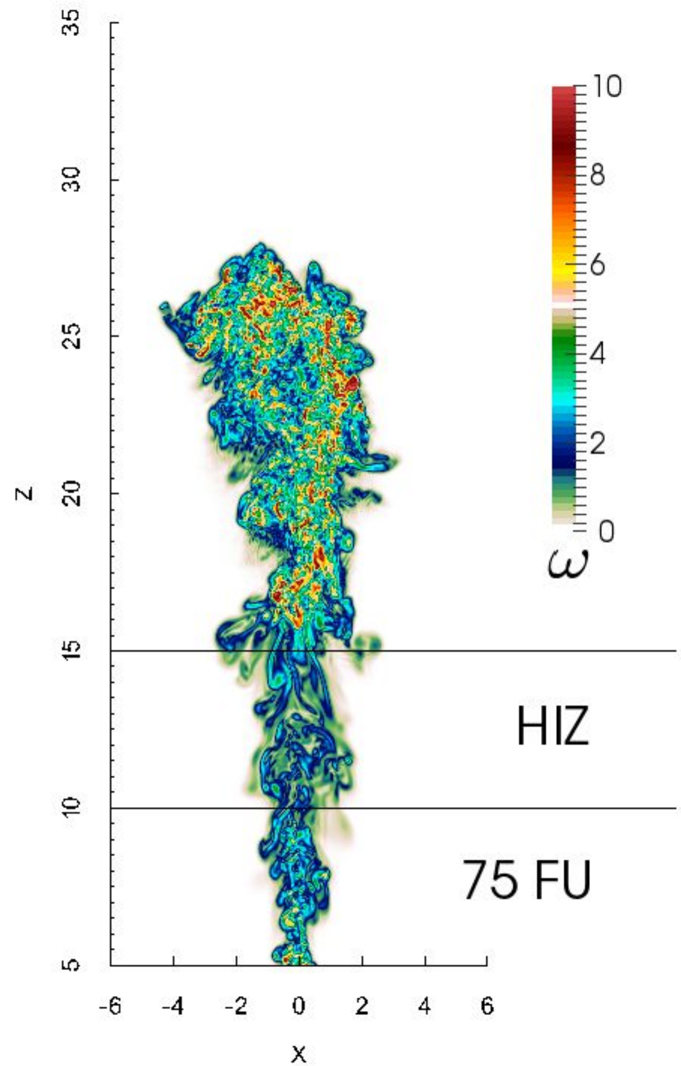
Z
X
ω
HIZ
67.5 FU

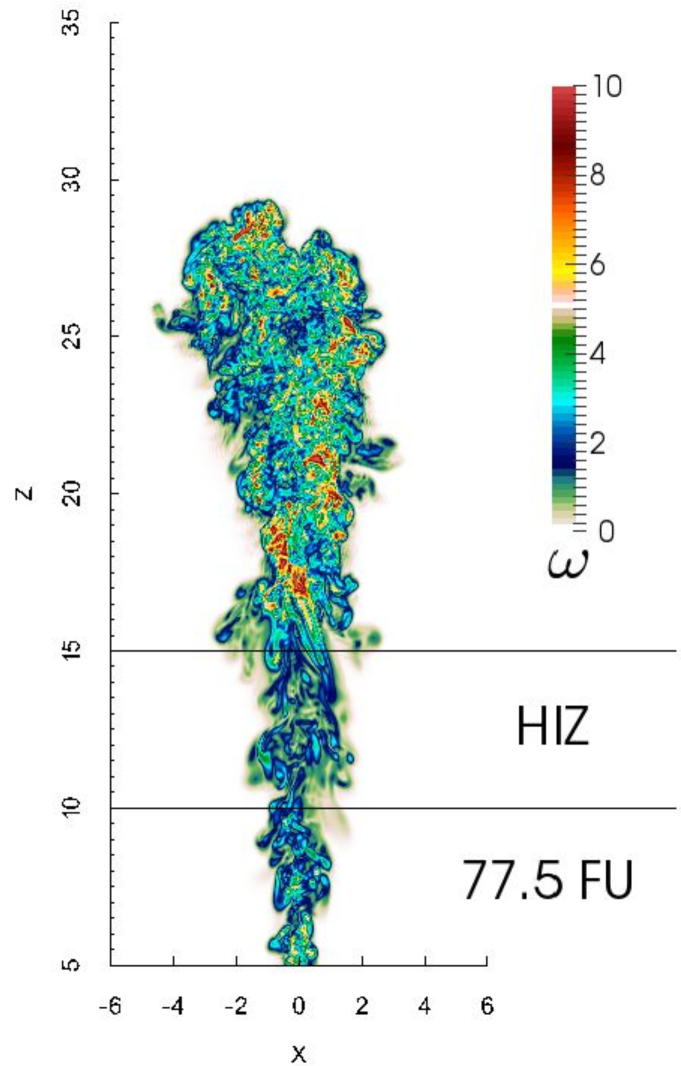


35
30
25
20
15
10
5
Z
10
8
6
4
2
0
ω
HIZ
70 FU
-6
-4
-2
0
2
4
6
X

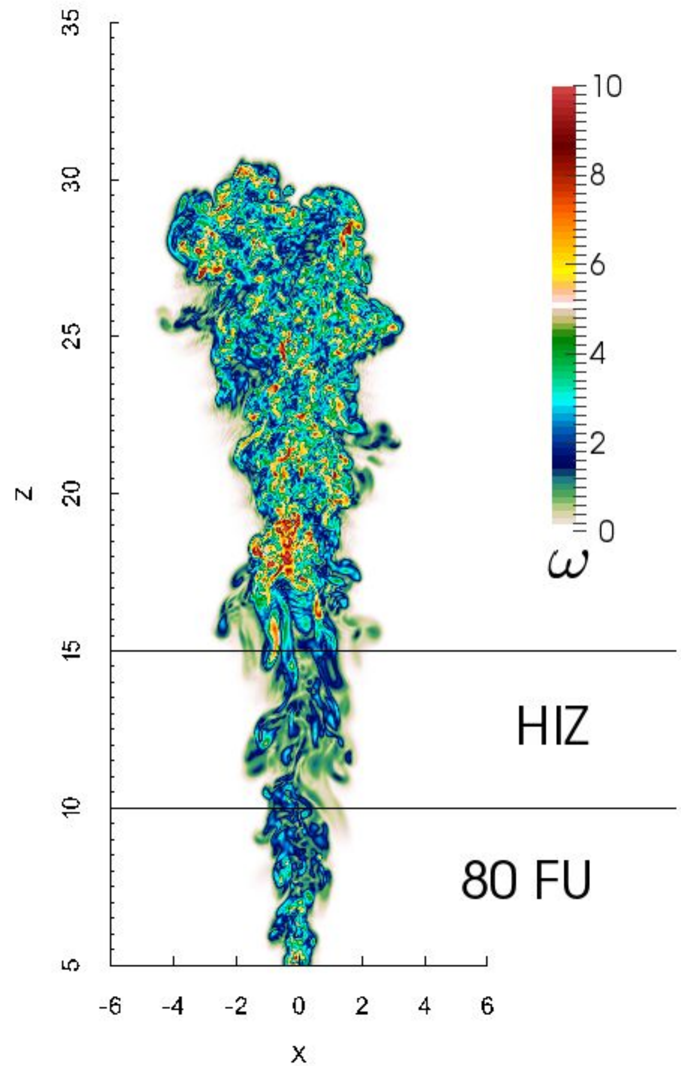


HIZ
72.5 FU
ω
z
x

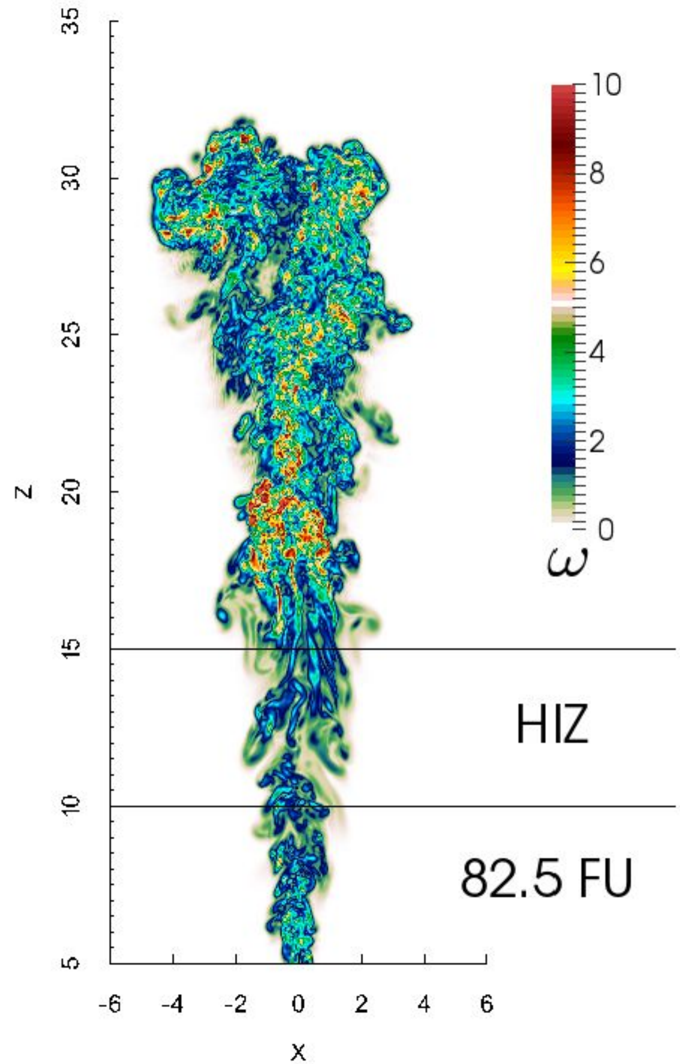

Z
X
35
30
25
20
15
10
5
-6
-4
-2
0
2
4
6
10
8
6
4
2
0
ω
HIZ
75 FU



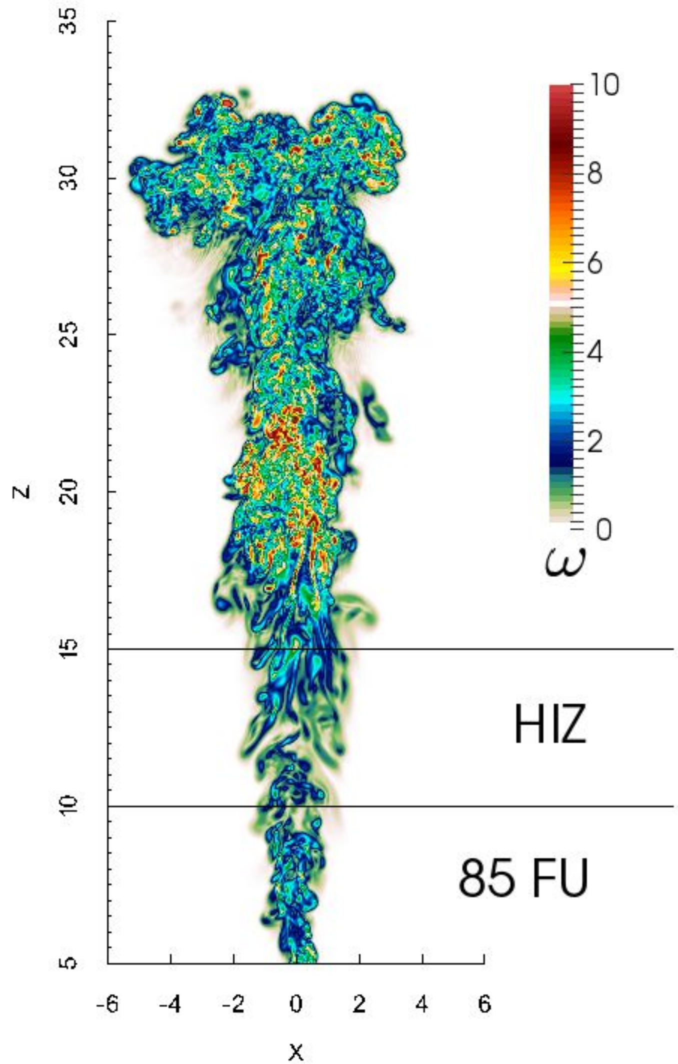
10
8
6
4
2
0
ω
HIZ
77.5 FU
Z
35
30
25
20
15
10
5
X
-6
-4
-2
0
2
4
6



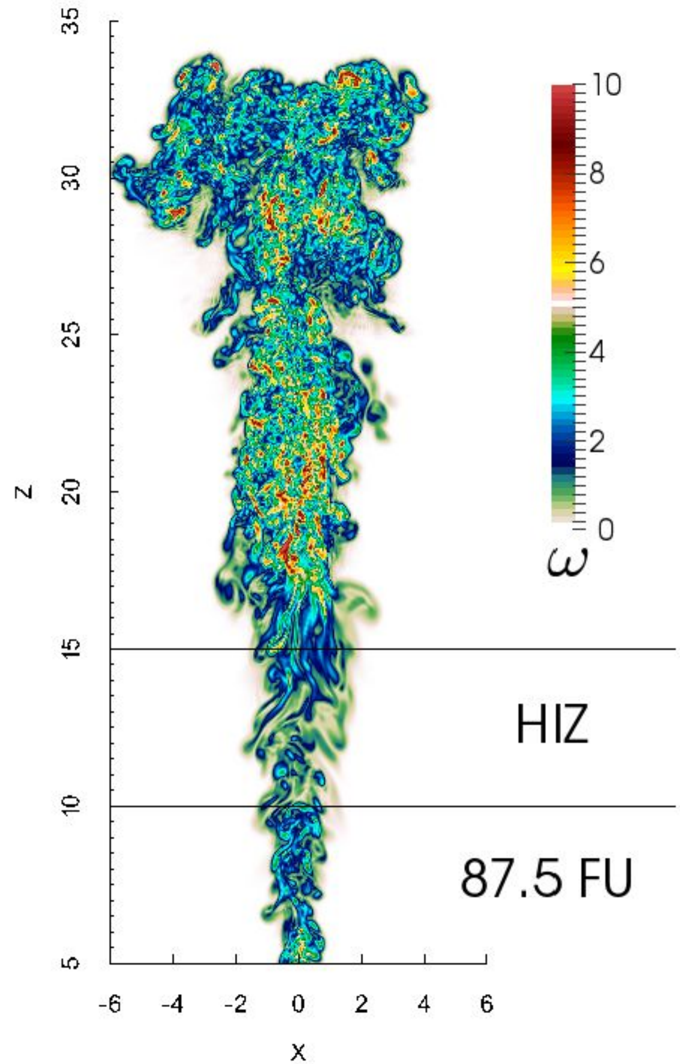
35
30
25
20
15
10
5
Z
-6 -4 -2 0 2 4 6
X
10
8
6
4
2
0
ω
HIZ
80 FU



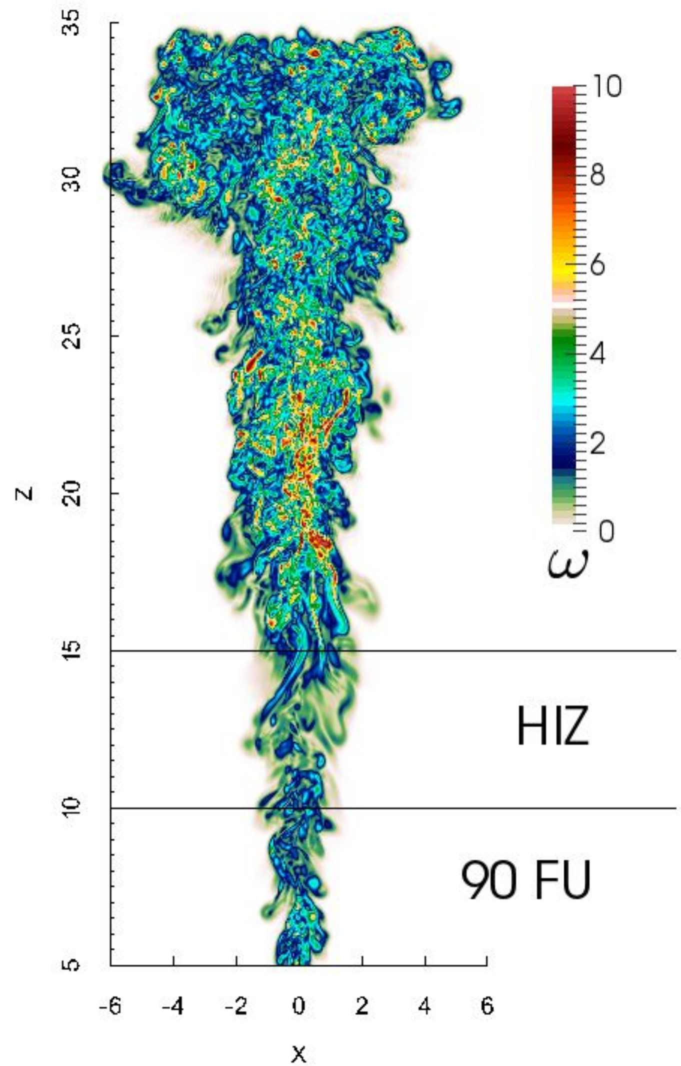
35
30
25
20
15
10
5
Z
-6
-4
-2
0
2
4
6
X
10
8
6
4
2
0
ω
HIZ
82.5 FU



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



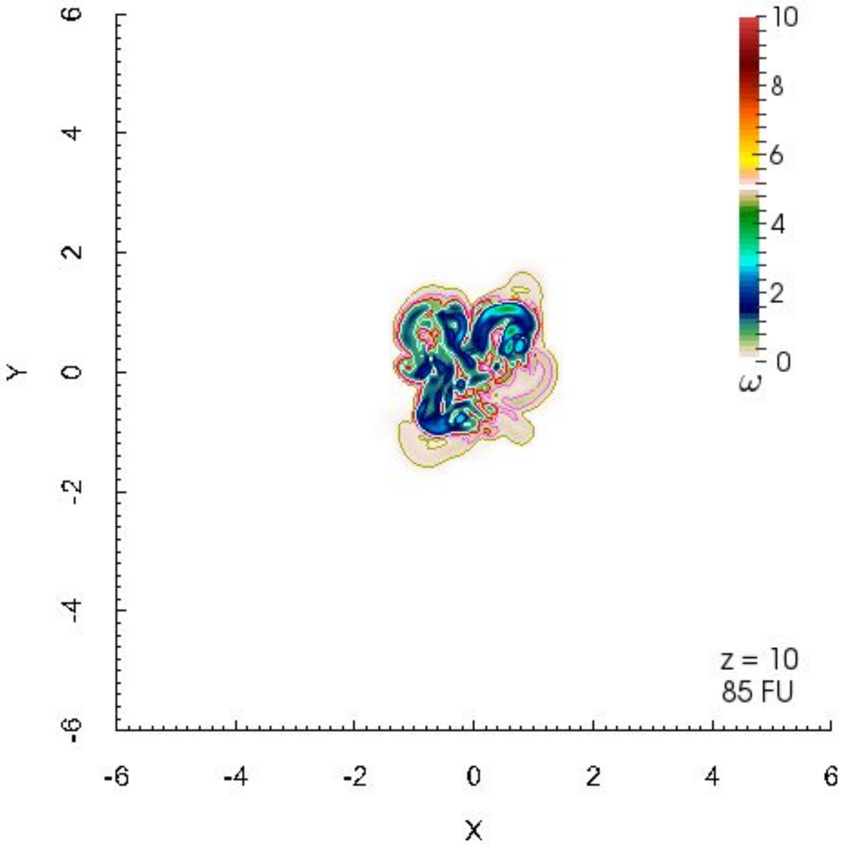
35
30
25
20
15
10
5
z
-6
-4
-2
0
2
4
6
x
10
8
6
4
2
0
ω
HIZ
87.5 FU

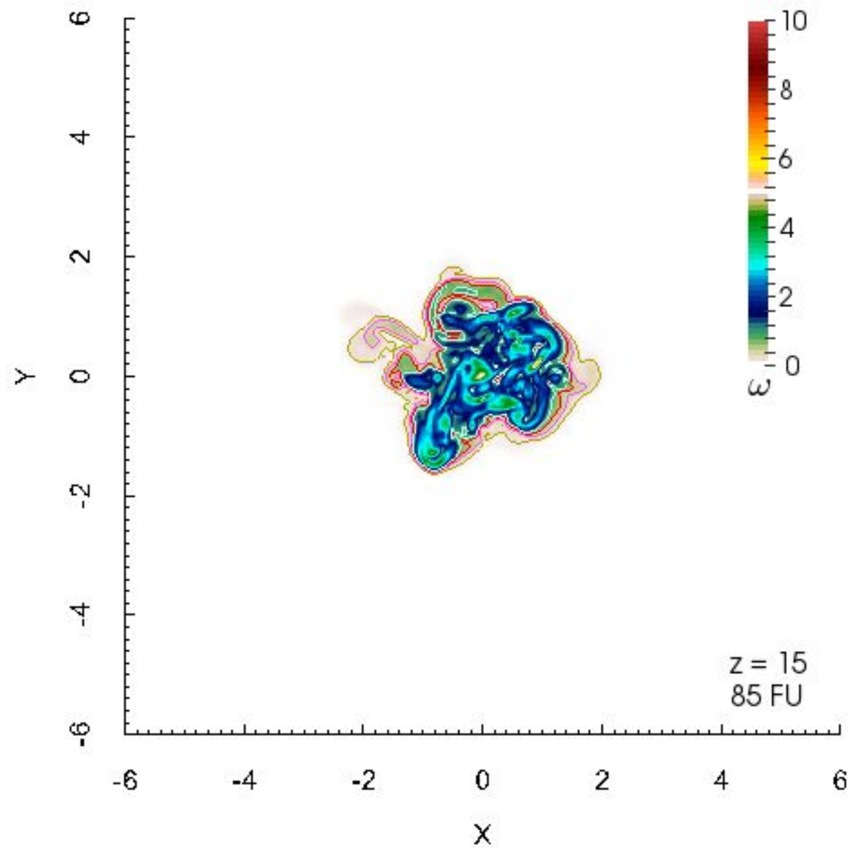


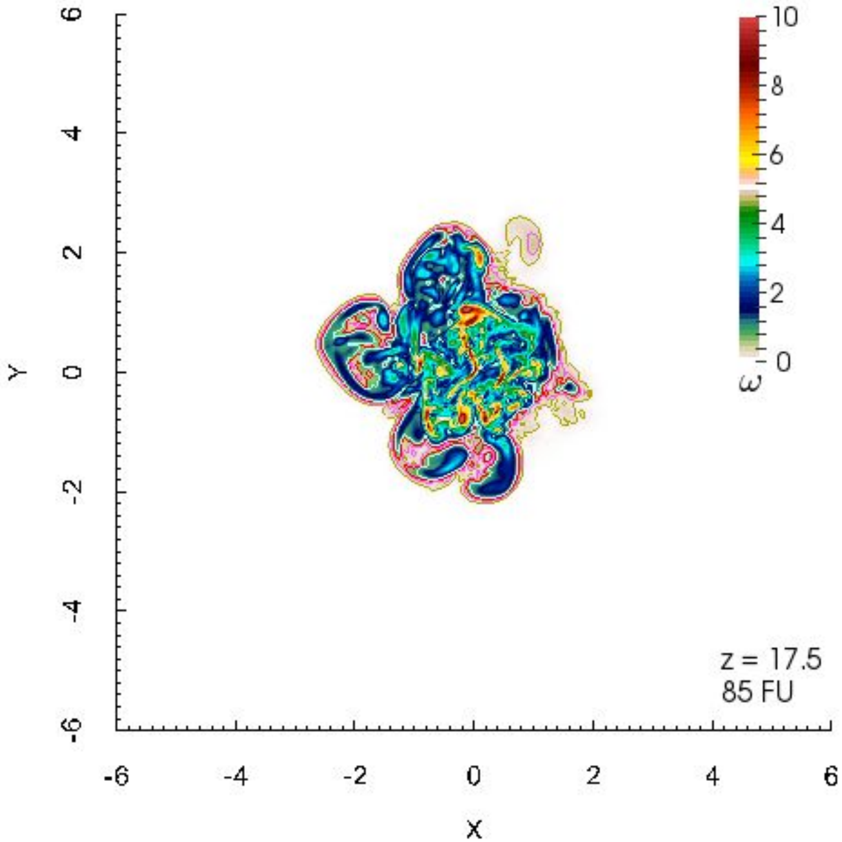
35
30
25
20
15
10
5
z
-6
-4
-2
0
2
4
6
x
10
8
6
4
2
0
ω
HIZ
90 FU

Diametral cross-sections

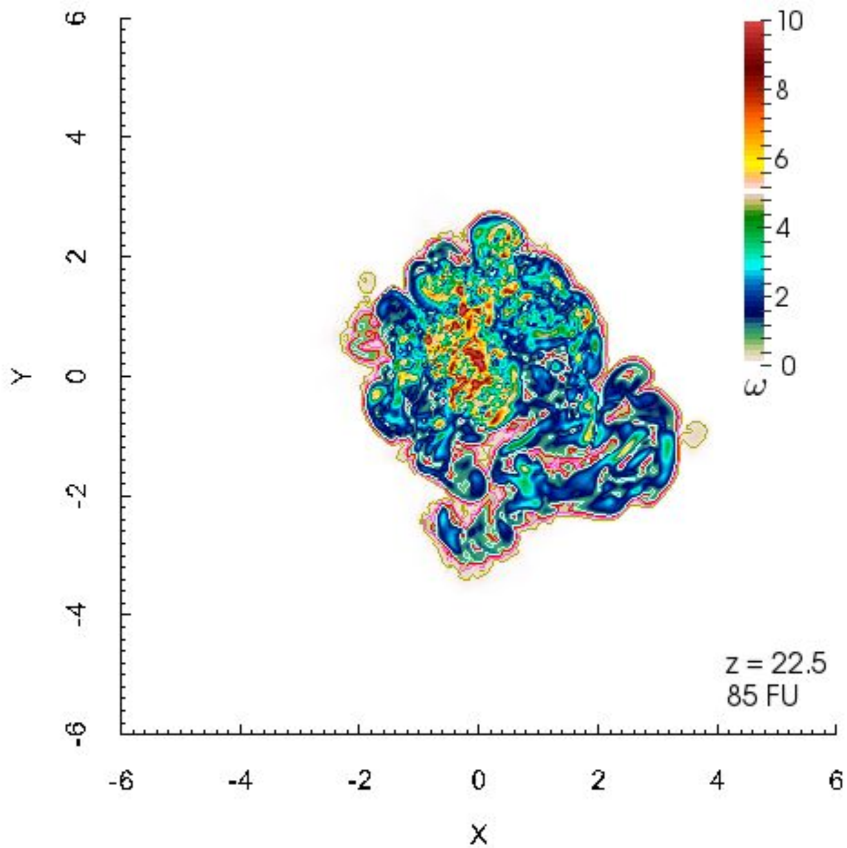
at 85 FU, with z


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

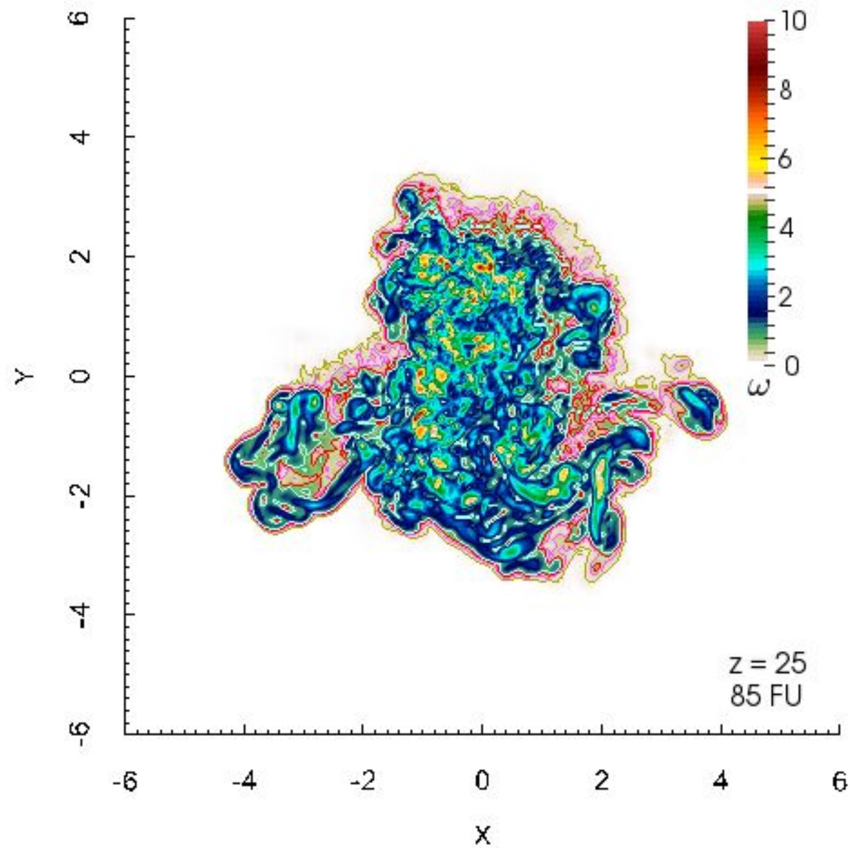

Y
X
ω
z = 15
85 FU



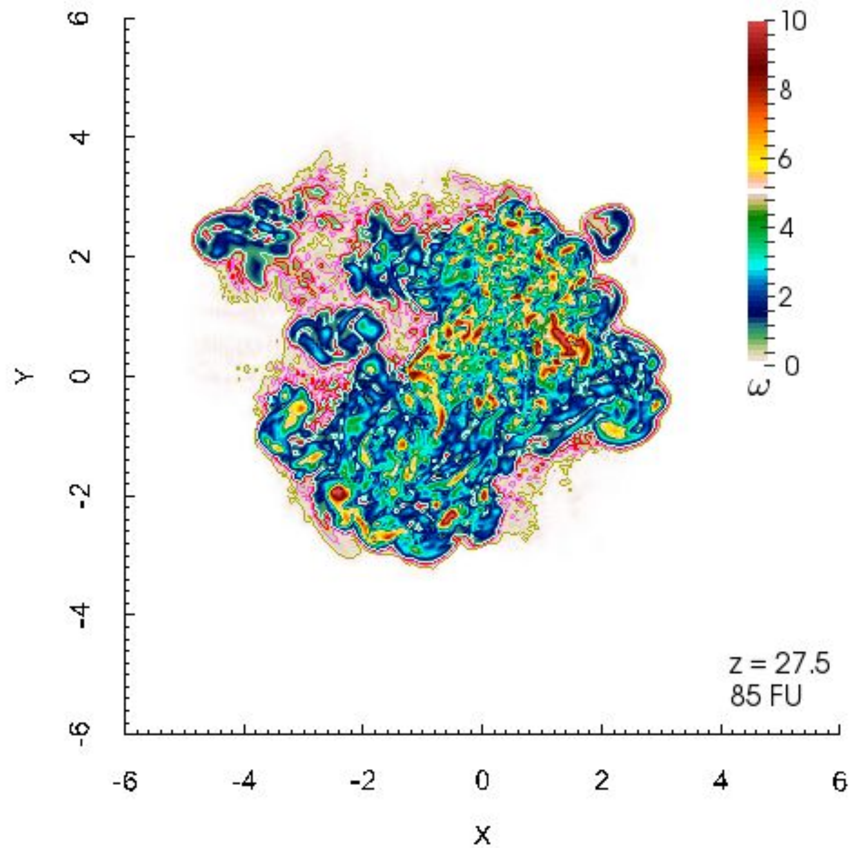
6
4
2
0
-2
-4
-6
Y
X
10
8
6
4
2
0
ω
z = 17.5
85 FU



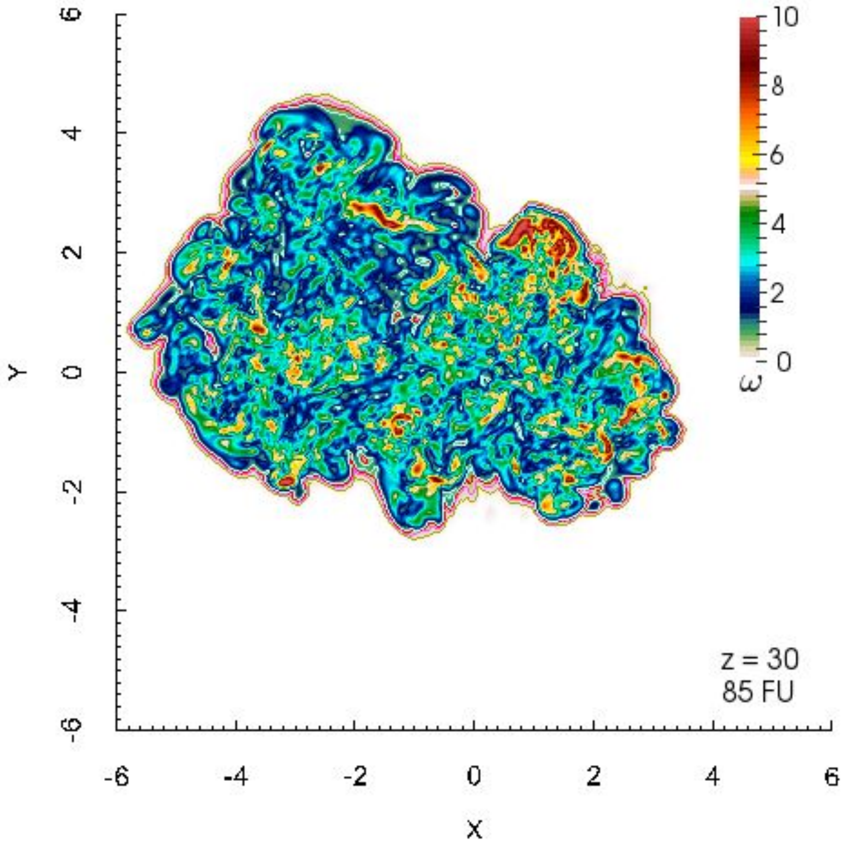
z = 22.5
85 FU
ω
X
Y



6
4
2
0
-2
-4
-6
Y
-6
-4
-2
0
2
4
6
X
10
8
6
4
2
0
ω
z = 25
85 FU

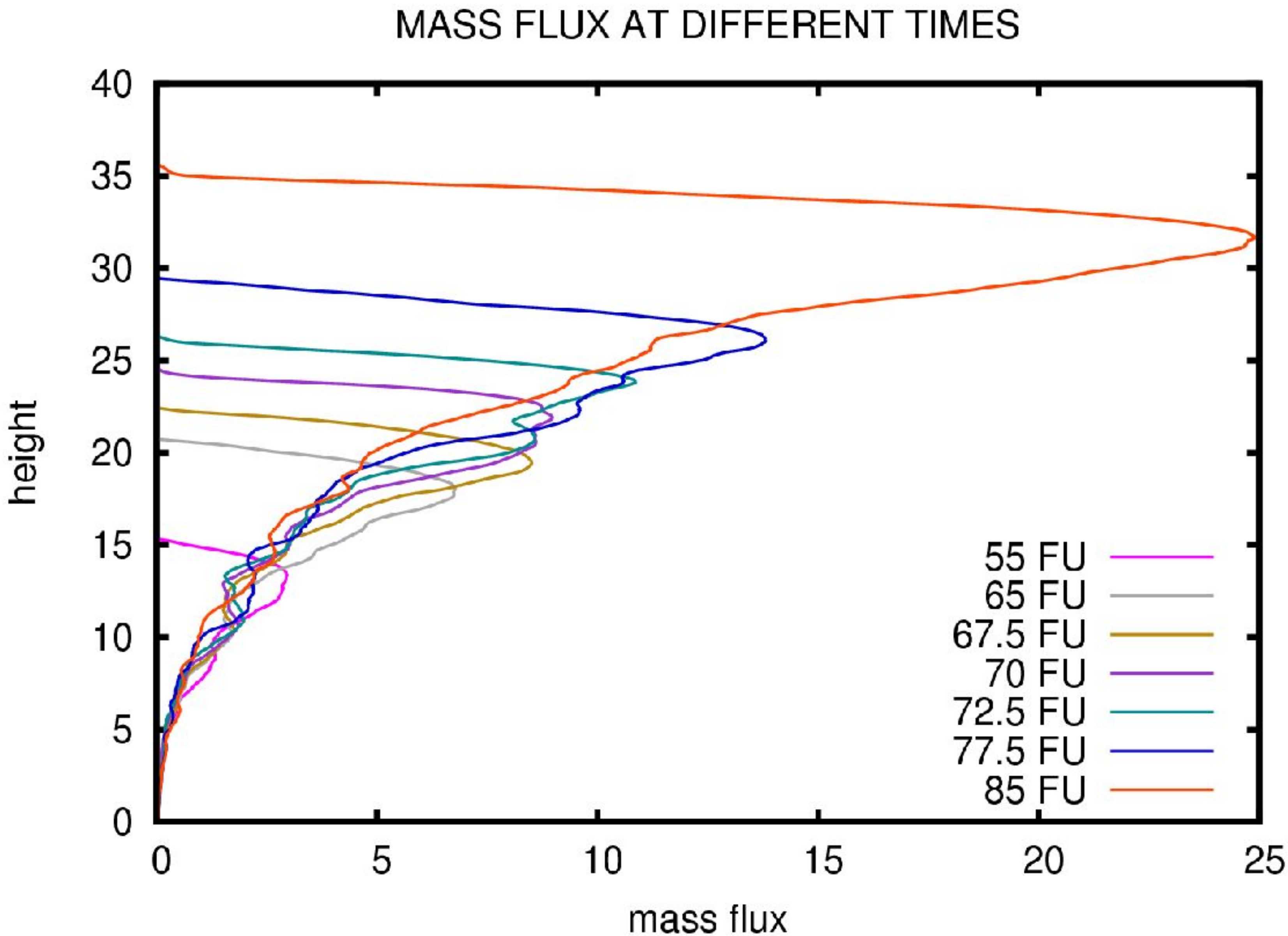


Y
X
ω
z = 27.5
85 FU

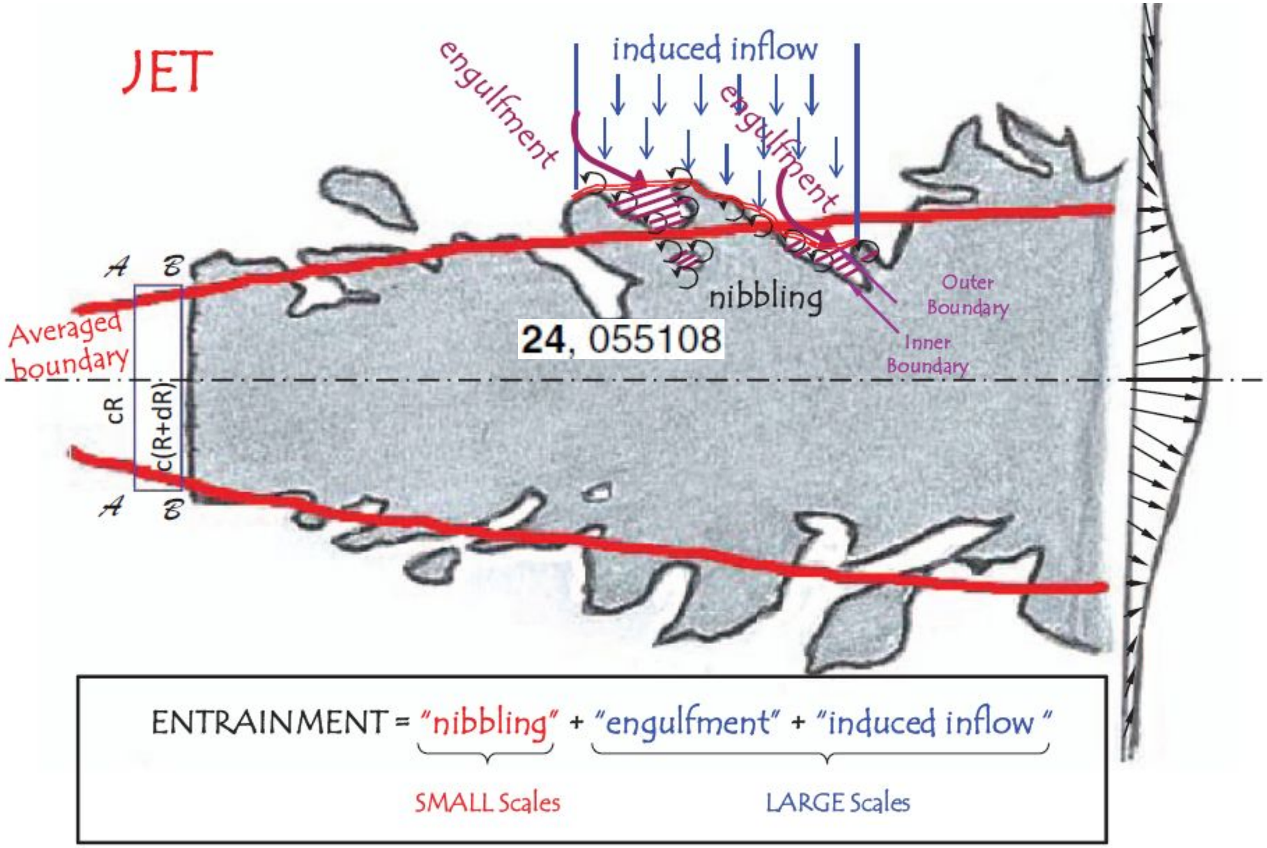


10
8
6
4
2
0
ω
Y
X
z = 30
85 FU

ENTRAINMENT DYNAMICS

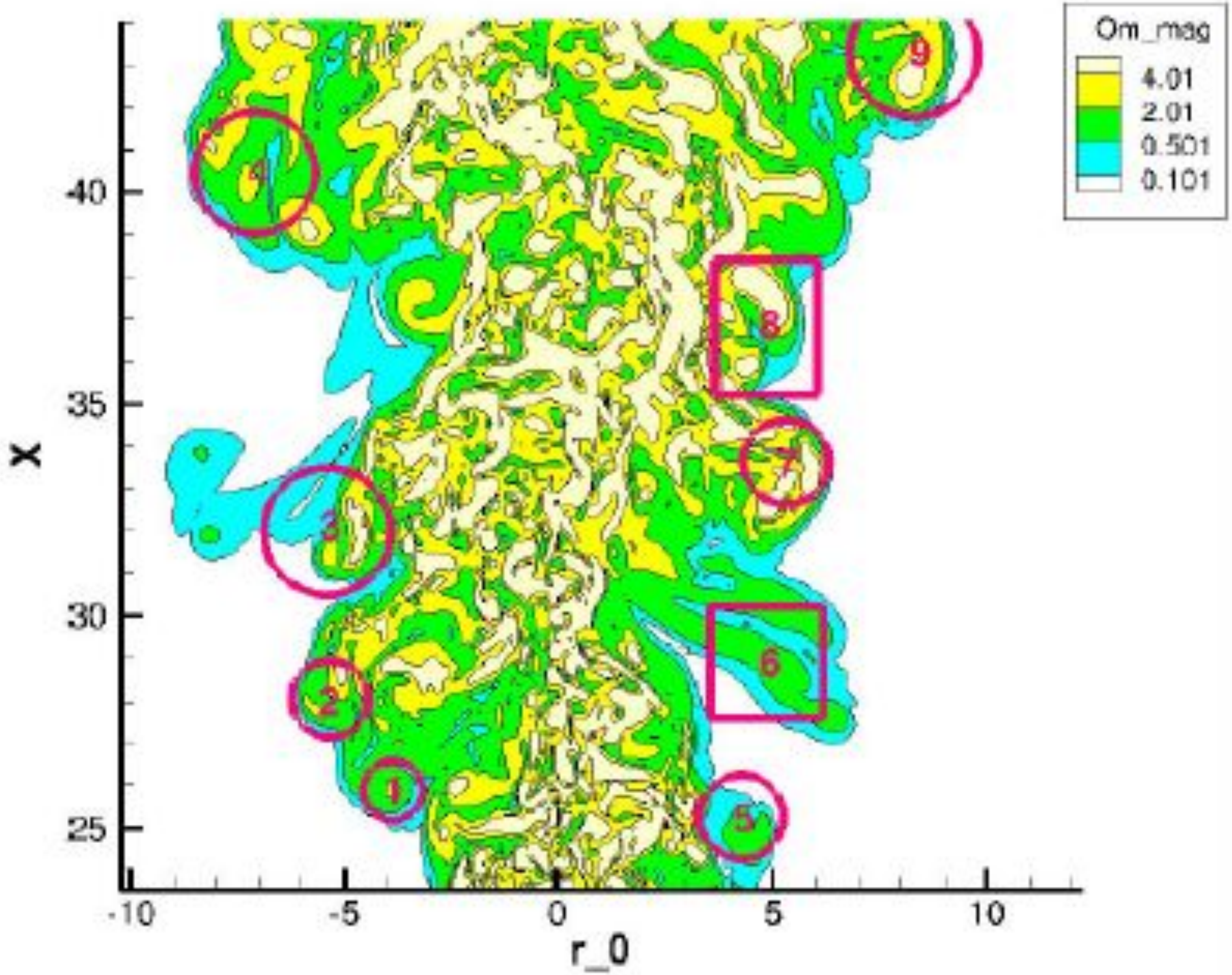

MASS FLUX AT DIFFERENT TIMES
height
mass flux
0
5
10
15
20
25
30
35
40
0
5
10
15
20
25
55 FU
65 FU
67.5 FU
70 FU
72.5 FU
77.5 FU
85 FU

ONE VIEW OF ENTRAINMENT

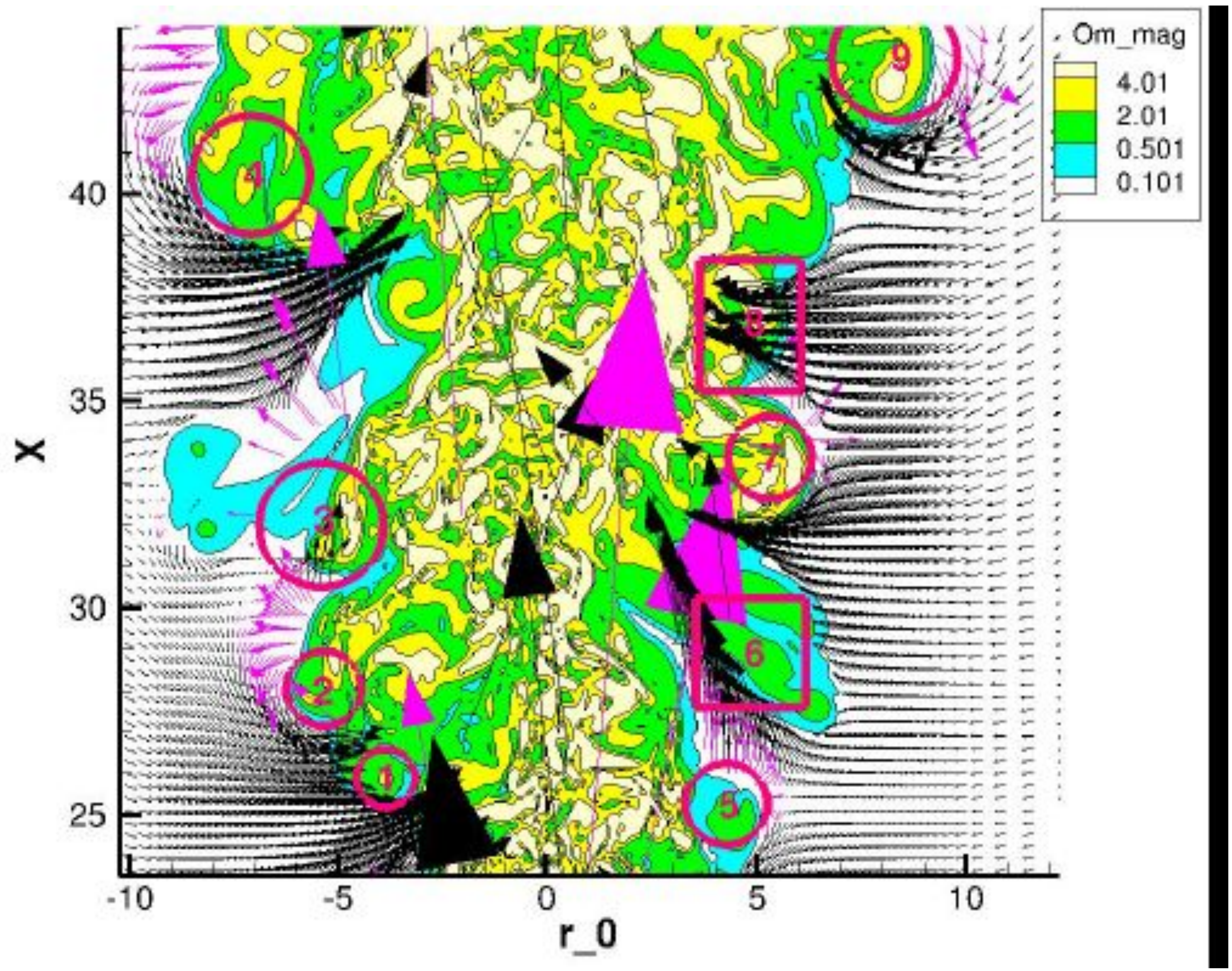


Philip and Marusic, 2012,PoF **24**

AXIAL Section : Vorticity field

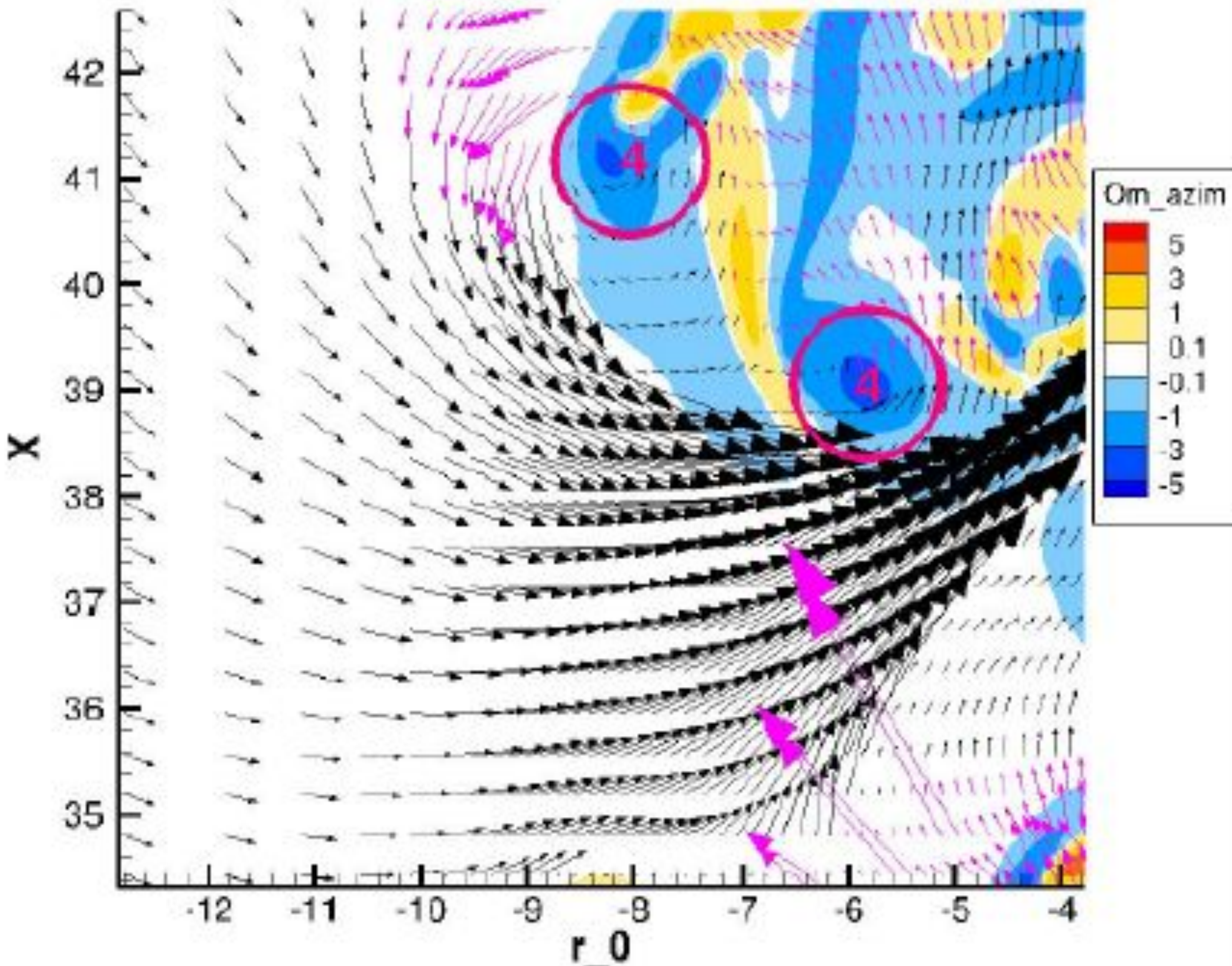


ANOTHER VIEW OF ENTRAINMENT



AXIAL Section : Velocity & Vorticity fields

AZIMUTHAL OMEGA AND INFLOW ACROSS EDGE NEAR JET BOUNDARY



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 have all ‘seemed’ based on ‘fact’ ?
- Computer simulations suggest that the

  baroclinic torque drives the cumulus flow engine

Conclusions

- 3D Navier-Stokes solver capable of simulating cloud flow was developed and validated.
- The significant role played by the heat distribution in determining the shape of any cumulus flow.
- Effect of off-source buoyancy addition and baroclinic torque on the structure of the flow was studied.
- Five 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.
- Key role of vorticity, baroclinic torque demonstrated
- Cumulus congestus is a special class of Transient Diabatic Plumes

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Thank you for listening !