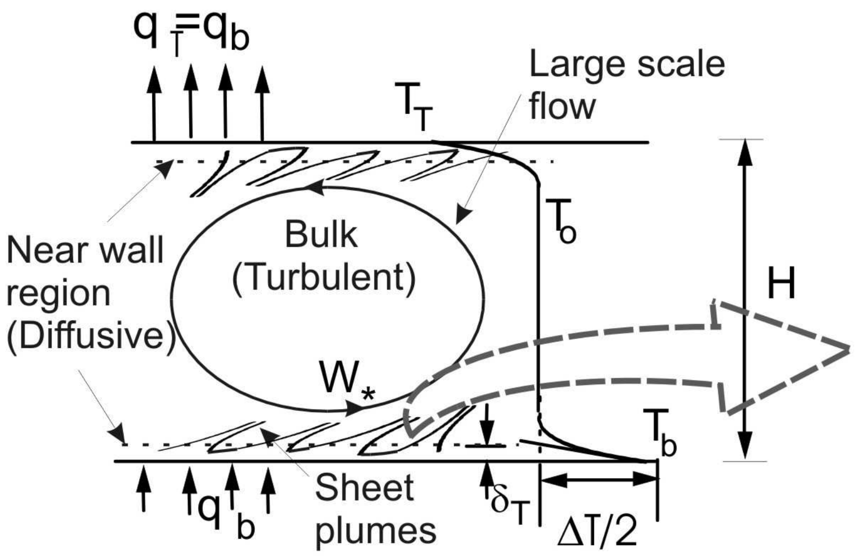
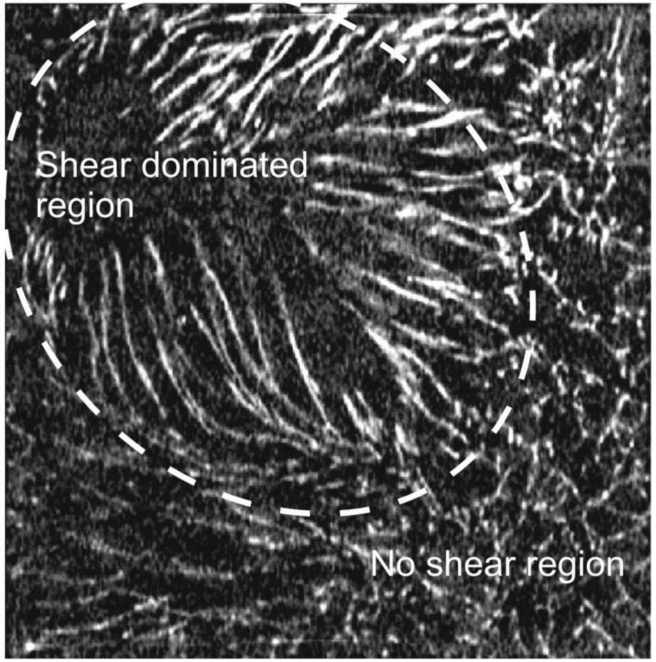
On separating Plumes from Boundary Layers in Turbulent Convection

Baburaj A. Puthenveettil[1], K. Vipin[1], R. Vishnu[2], K. Sanal Mohanan[1], and A. Sameen[2]

[1]Fluid Mechanics Laboratory
Dept. of Applied Mechanics,
Indian Institute of Technology Madras.

[2]Dept. of Aerospace Engineering,
Indian Institute of Technology Madras.

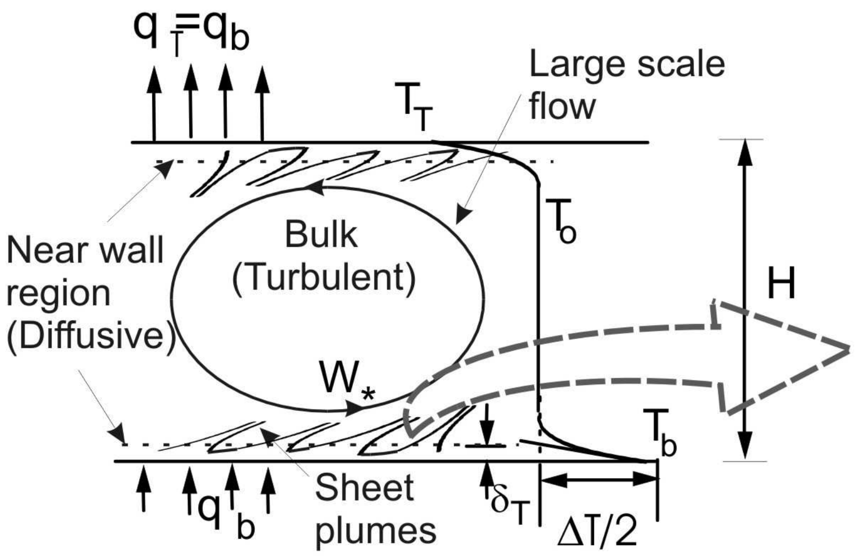


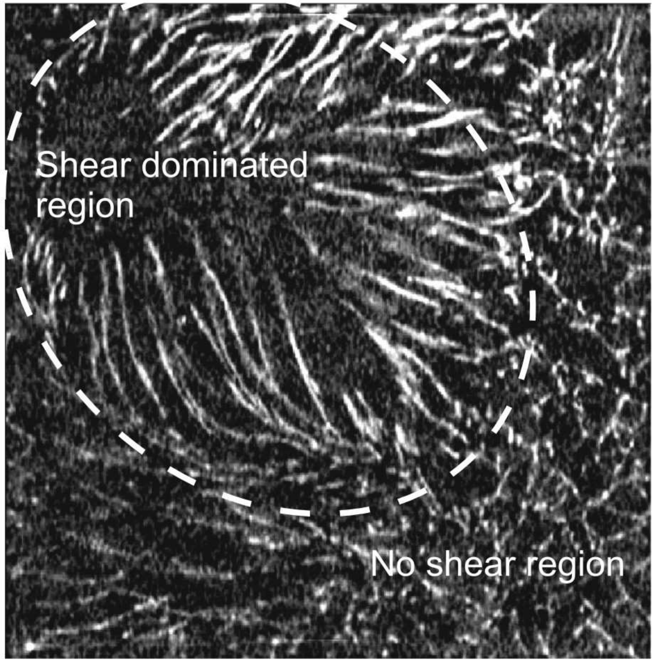


Steady, turbulent Rayleigh Benard Convection (RBC)

$$Nu = f(Ra, Pr, AR), \text{ where,}$$

$$Nu = \frac{q}{k\Delta T/H}, \; Ra_w = \frac{g\beta\Delta T_w H^3}{\nu\alpha}, \; Pr = \frac{\nu}{\alpha}, \; AR = \frac{L}{H} \text{ and } Z_w = \left(\frac{\nu\alpha}{g\beta\Delta T_w}\right)^{1/3}.$$



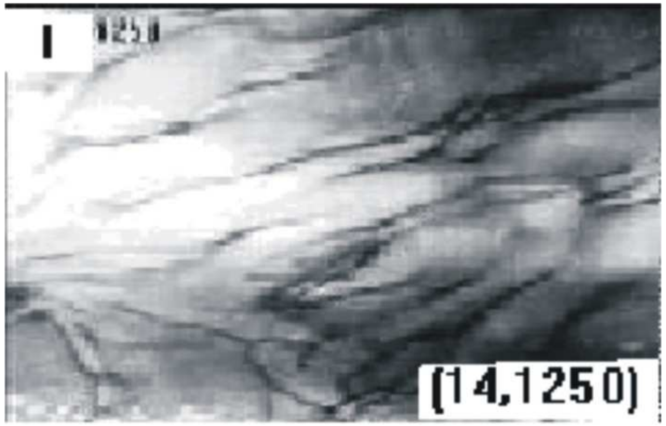


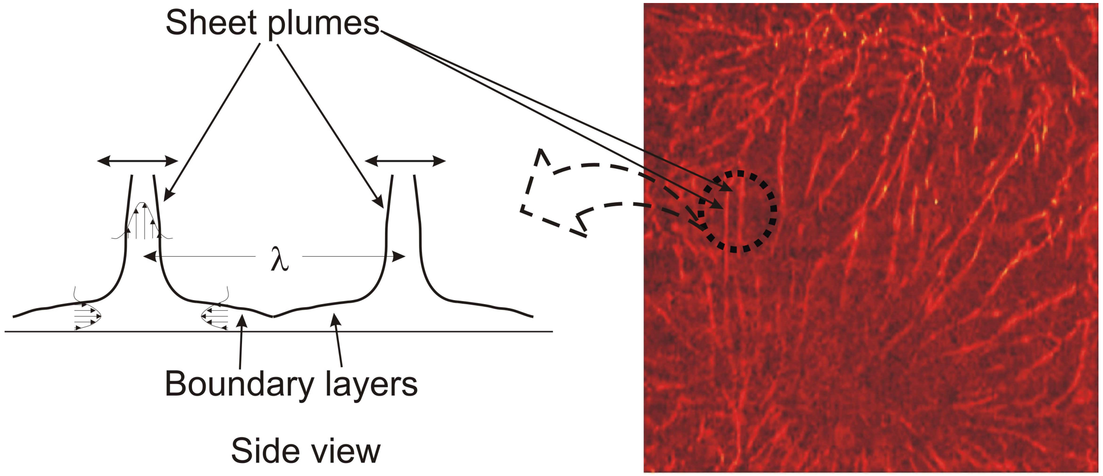
Steady, turbulent Rayleigh Benard Convection (RBC)

$$Nu = f(Ra, Pr, AR), \text{ where,}$$

$$Nu = \frac{q}{k\Delta T/H},\ Ra_w = \frac{g\beta\Delta T_w H^3}{\nu\alpha},\ Pr = \frac{\nu}{\alpha},\ AR = \frac{L}{H} \text{ and } Z_w = \left(\frac{\nu\alpha}{g\beta\Delta T_w}\right)^{1/3}.$$

Nature of boundary layers & its role in flux scaling is not clear.





(a) Ra= 2.25×10^8. *(Theerthan & Arakeri, Phy. Fluids,12)* (b) Ra= 1.2×10^{11}. *(Puthenveettil & Arakeri, JFM, 609)*

- Sheet plumes that form ($t_i \sim Z_w^2/\alpha$) and merge ($\overline{V}_m \sim \nu/Zw$) subjected to external shear ($W^* \sim (g\beta qH)^{1/3}$) (Gunasegarane & Puthenveettil, JFM,749,2014.)
- At any instant the mean plume spacing $\lambda = C_1 Z_w Pr^{n_1}$ and the total plume length $L_p = A/\lambda$ (Puthenveettil et al JFM 685).
- Due to this, the nature of boundary layers inferred from averaged vertical velocity profiles are suspect.

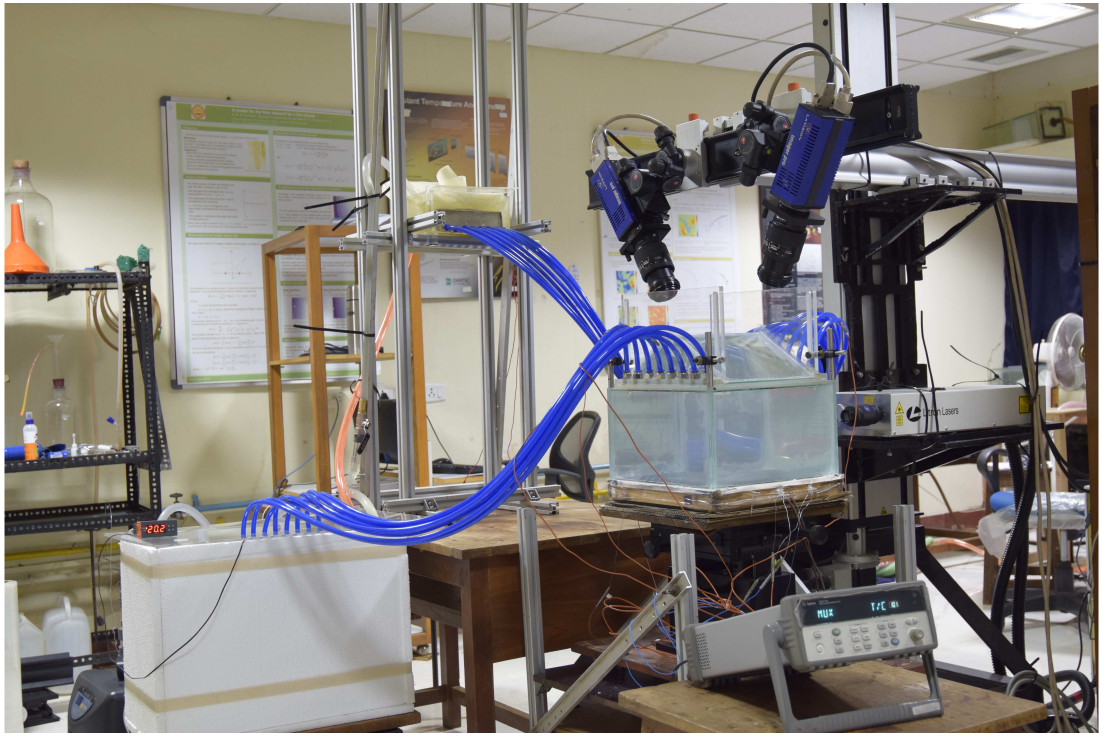
Separating plumes from BLs in instantaneous velocity fields are needed.

1. Local measurement based :
2. Temperature field based : $T' > c\sqrt{\overline{T'^2}}$ (Gastine et al., JFM), Shishkina
3. Based on correlation of temperature and velocity :
   $T' > c\sqrt{\overline{T'^2}} + wT > cNu$(Huang et al. PRL, 111, 2013), $wT' > 0$.

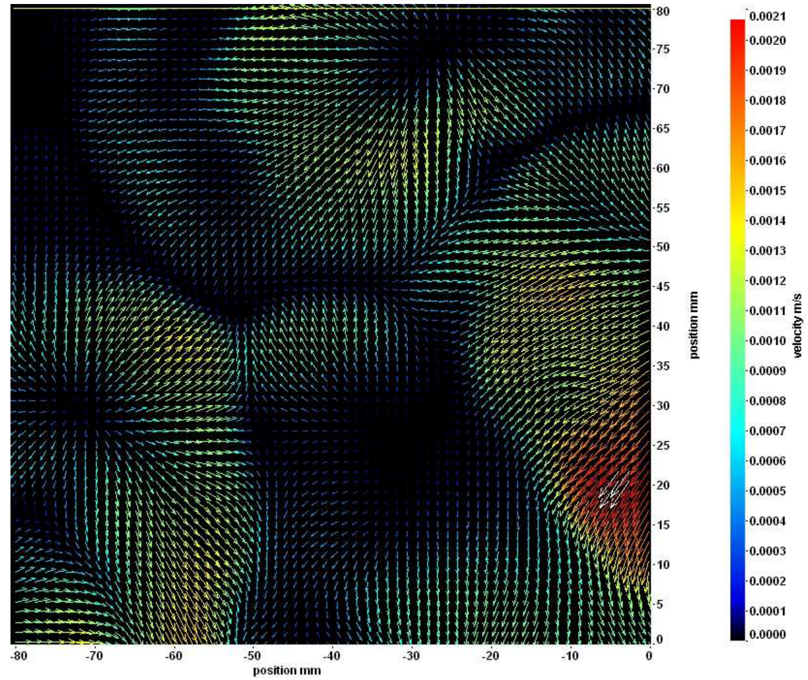
No purely velocity based criterion available.

Objective :

- To develop a velocity based criterion for separating plumes from boundary layers so that
- PIV velocity fields can be used to understand
- the nature of boundary layers and
- the dynamics of plumes.



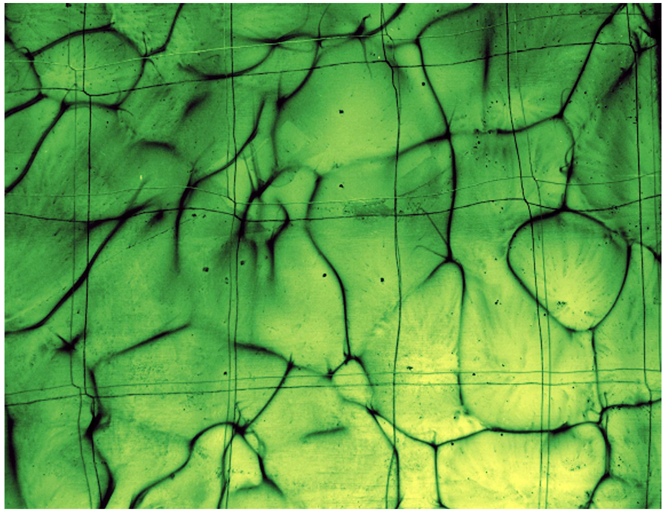
(a) Experimental Setup for PIV

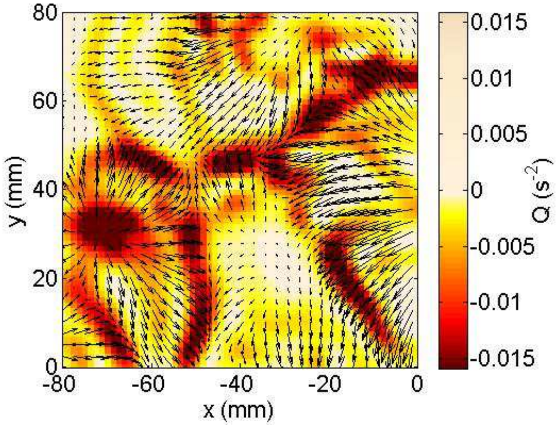


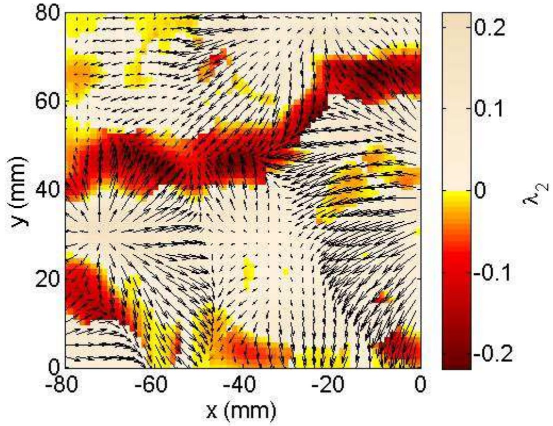
(b)A typical 2D vector field

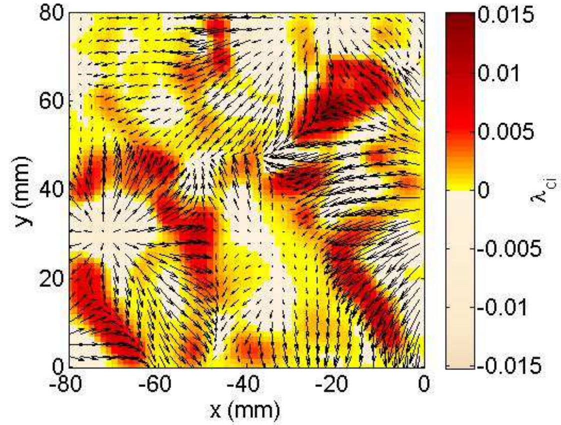
Parameters	$Ra_w = 7.5 \times 10^5$	$Ra_w = 1.4 \times 10^9$
Pr	5.3	4.04
δ_{PB}(mm)	4.8	3.81
$\delta_{NC}(mm)$	5.6	1.4
h_m(mm)	3.5	1.2

We measure instantaneous velocities in a horizontal plane within boundary layers.

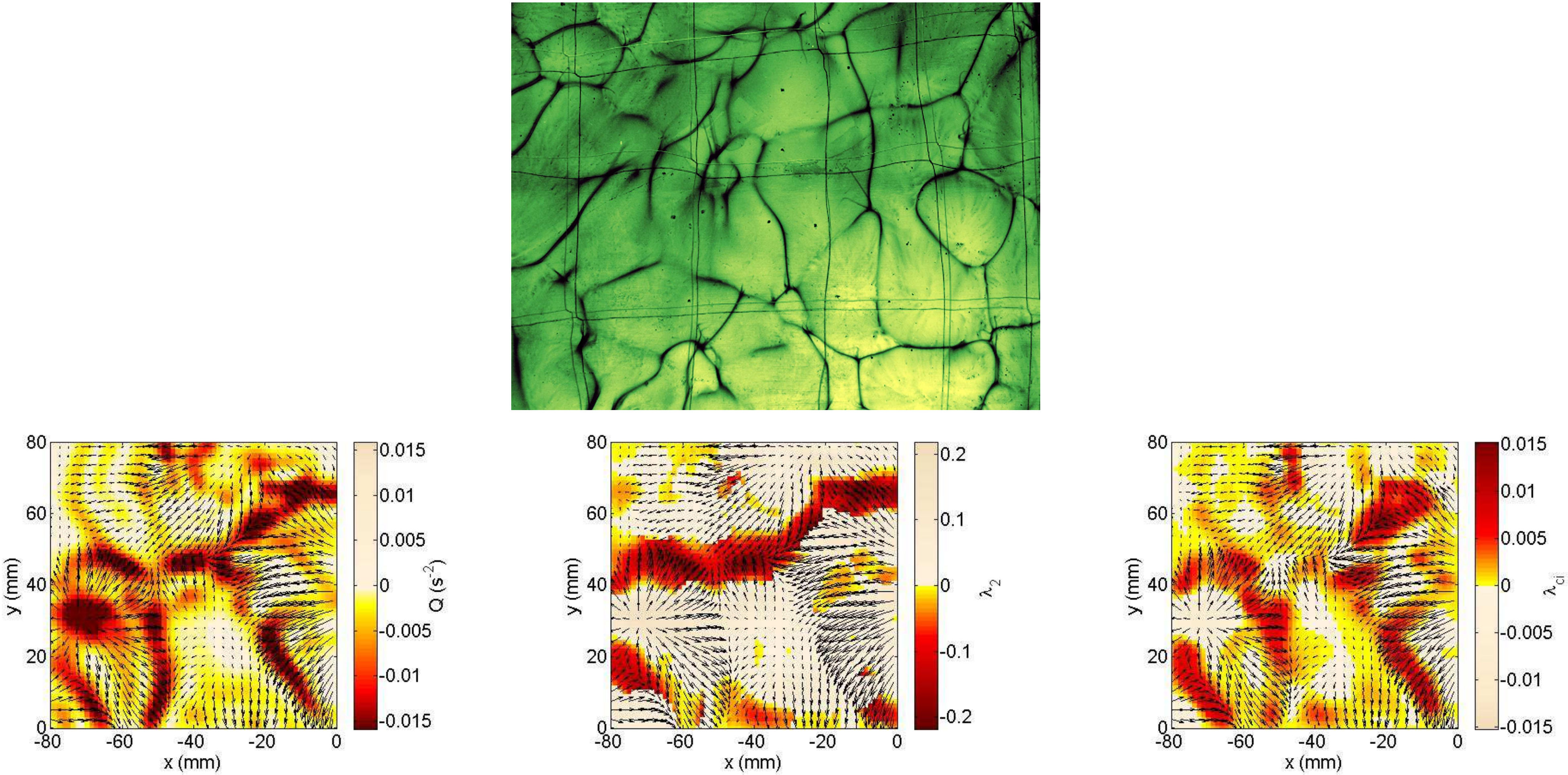






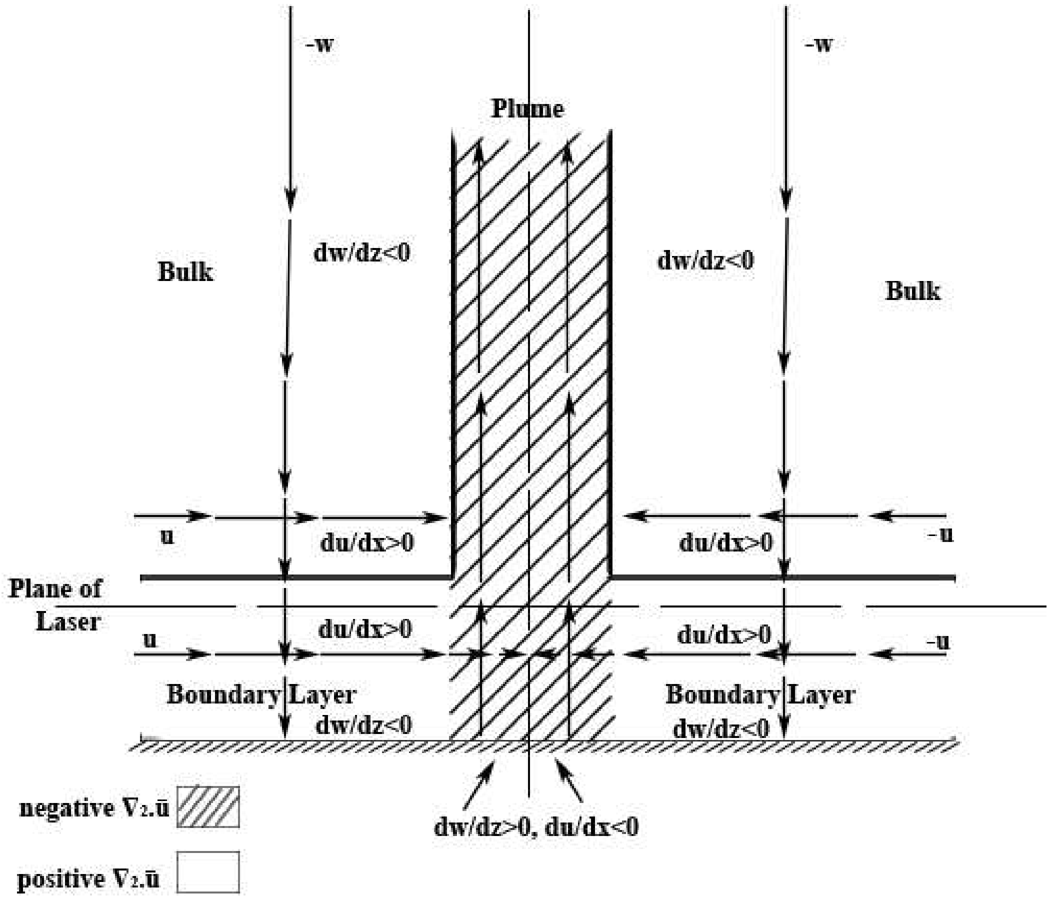


$Ra_w = 7.5 \times 10^5$(a) Dye visualisation (b) Q criterion (c) λ_2 criterion (d) Swirling strength criterion



$Ra_w = 7.5 \times 10^5$(a) Dye visualisation (b) Q criterion (c) λ_2 criterion (d) Swirling strength criterion

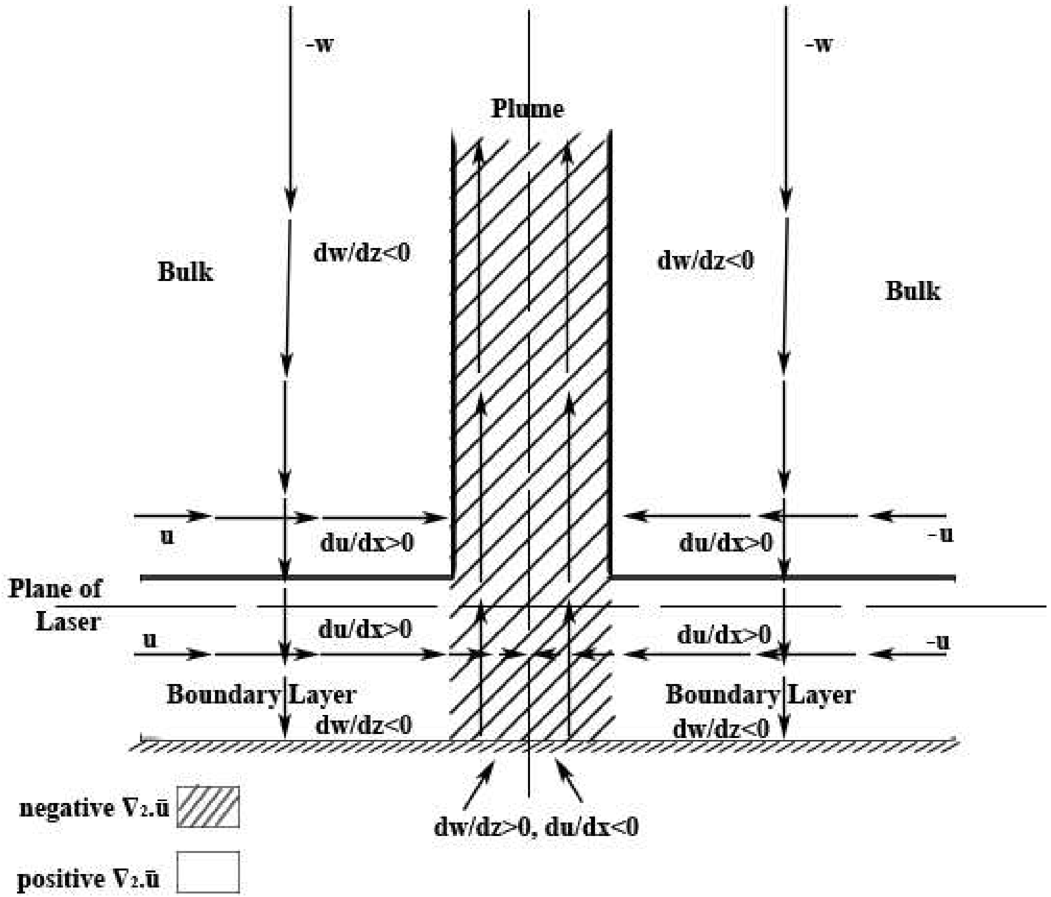
None of the criteria is satisfactory



Schematic of velocity gradients and values of $\overline{\nabla}_H \bullet \overline{V}$ criterion

Flow near the plates separates into two regions :

1. Plumes where $\partial w/\partial z > 0$ and $\partial u/\partial x < 0 \Rightarrow \overline{\nabla}_H \bullet \overline{V} < 0$
2. Bulk and boundary layers where $\partial w/\partial z < 0$ and $\partial u/\partial x > 0 \Rightarrow \overline{\nabla}_H \bullet \overline{V} > 0$

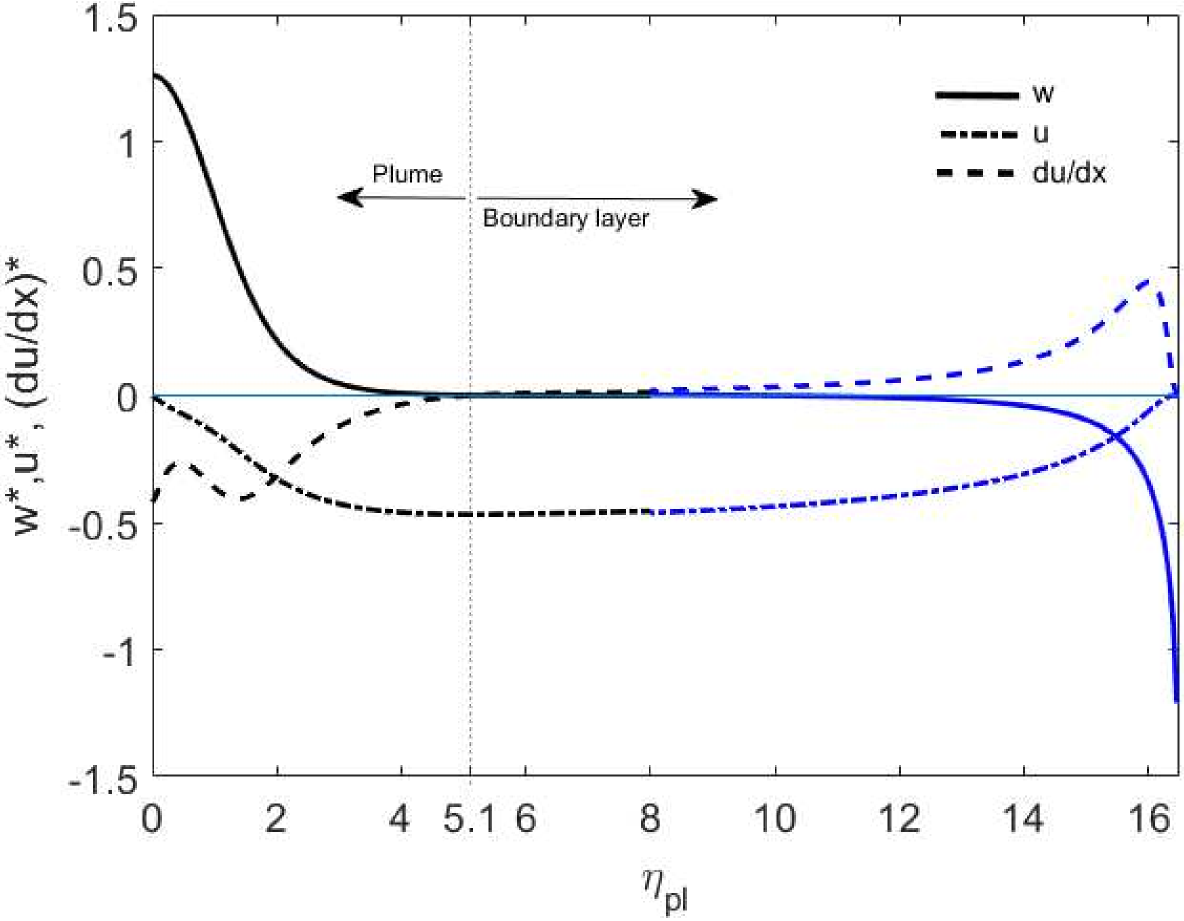


Schematic of velocity gradients and values of $\overline{\nabla}_H \bullet \overline{V}$ criterion

Flow near the plates separates into two regions :

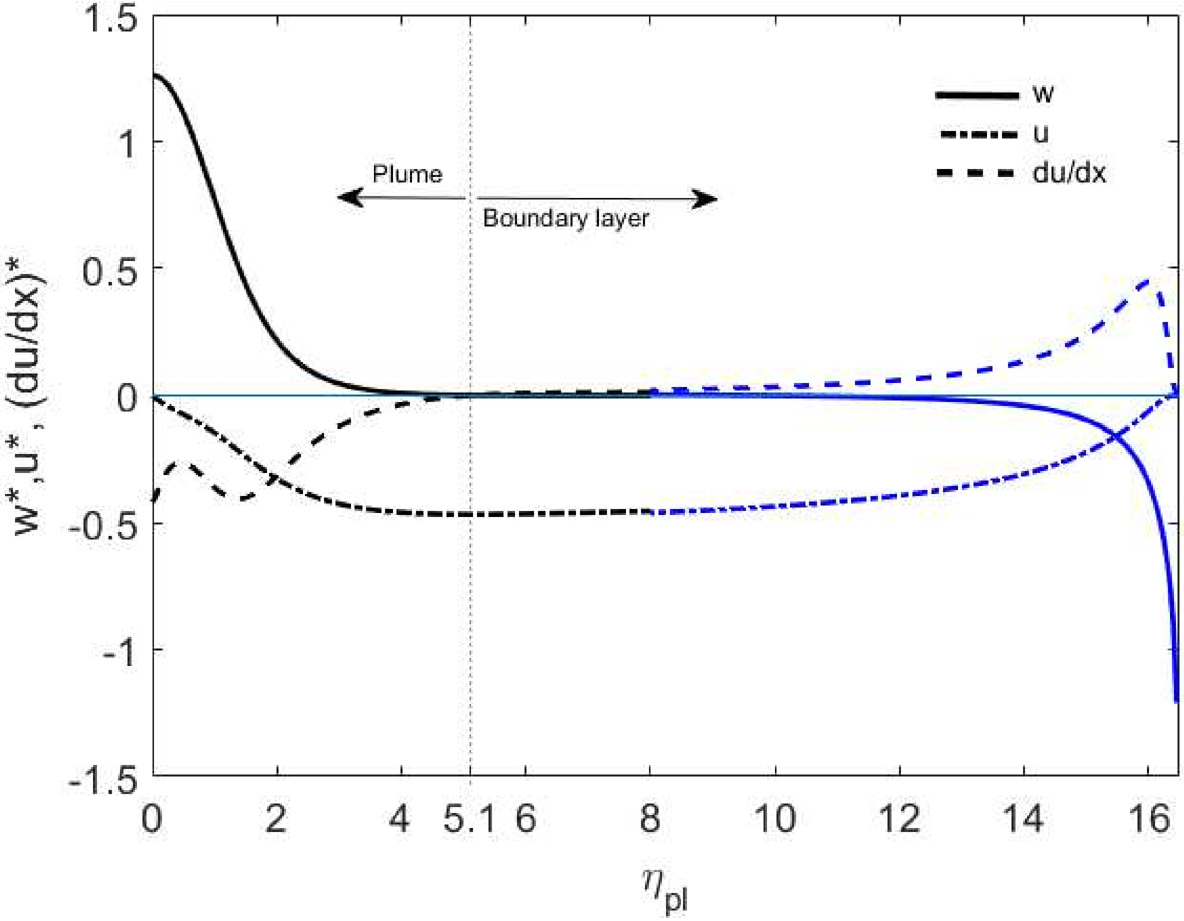
1. Plumes where $\partial w/\partial z > 0$ and $\partial u/\partial x < 0 \Rightarrow \overline{\nabla}_H \bullet \overline{V} < 0$
2. Bulk and boundary layers where $\partial w/\partial z < 0$ and $\partial u/\partial x > 0 \Rightarrow \overline{\nabla}_H \bullet \overline{V} > 0$

$\overline{\nabla}_H \bullet \overline{V}$ hence separates plume and non-plume regions



Similarity solution of laminar plume ⇒

$$w = 2\sqrt{g\beta N} z^{1/5} f'(\eta_{pl}), \quad \frac{\partial w}{\partial z} = \frac{2}{5z^{4/5}}\sqrt{g\beta N}(f'(\eta_{pl}) - 2\eta f''(\eta_{pl})) \quad (1)$$



Similarity solution of laminar plume $\Rightarrow$

$$w = 2\sqrt{g\beta N}z^{1/5}f'(\eta_{pl}), \quad \frac{\partial w}{\partial z} = \frac{2}{5z^{4/5}}\sqrt{g\beta N}(f'(\eta_{pl}) - 2\eta f''(\eta_{pl})) \quad (1)$$

From (1), $\overline{\nabla}_H \bullet \overline{V} = 0$ at plume edge$\Rightarrow$

$$w = 0;\ \partial w/\partial z = 0;\ \partial u/\partial x = 0;\ \partial w/\partial x = 0$$

For plumes, energy equation + continuity equation $\Rightarrow$

$$\overline{\nabla}_H \bullet \overline{V} = \frac{1}{\alpha T^2} wT\, \alpha \frac{\partial T}{\partial z} + \frac{1}{T}\frac{\partial}{\partial x}\left[uT - \alpha \frac{\partial T}{\partial x}\right]$$

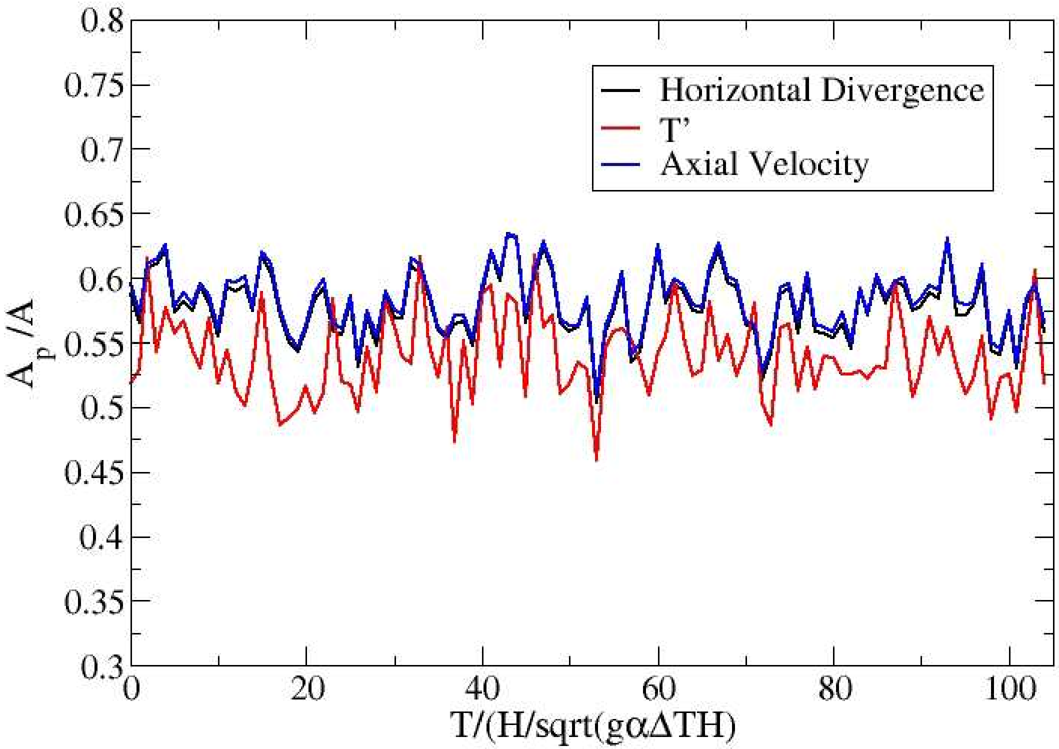
- The first term dominates and is -ve since $\frac{\partial T}{\partial z}$ is -ve inside plumes

For BLs, energy equation + continuity equation $\Rightarrow$

$$\overline{\nabla}_H \bullet \overline{V} = \frac{1}{\alpha T^2} uT\, \alpha \frac{\partial T}{\partial x} + \frac{1}{T}\frac{\partial}{\partial z}\left[wT - \alpha \frac{\partial T}{\partial z}\right]$$

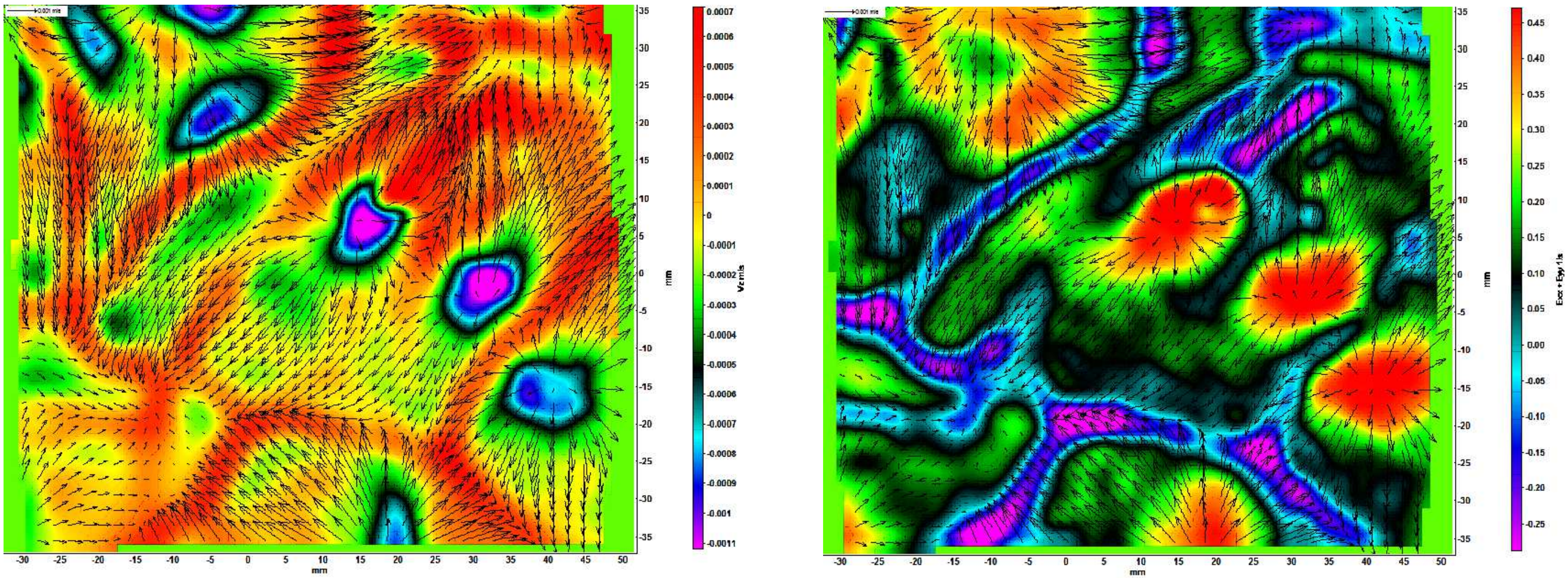
- The first term dominates and is +ve since $\frac{\partial T}{\partial z}$ is +ve inside BLs

Vertical (horizontal) Convective flux $\times$ conductive flux has -ve (+ve) sign inside plumes (BLs)



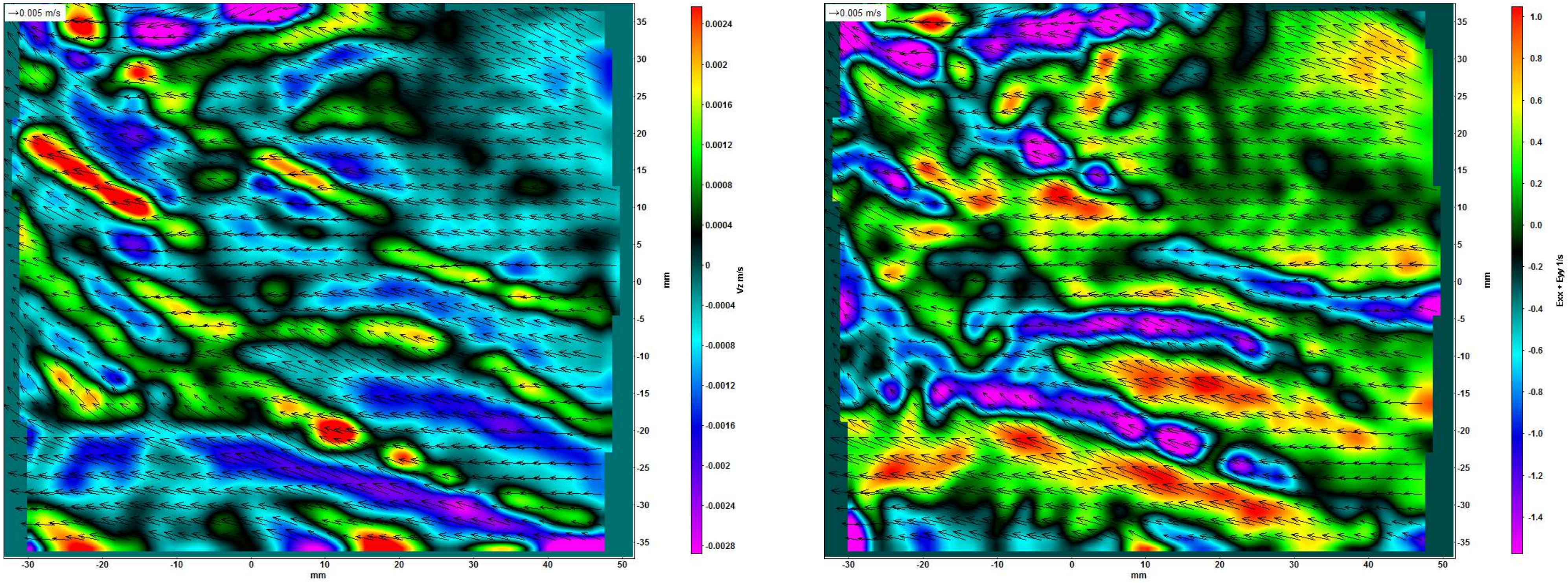
Instantaneous plume area fractions at $Ra_w = 2 \times 10^8$, $Pr = 1, D/H = 0.5$ at $z/H = 0.3 \times 10^{-2}$

In the absence of impingement/large scale flow +ve w fields match -ve $\overline{\nabla}_H \bullet \overline{V}$ fields.



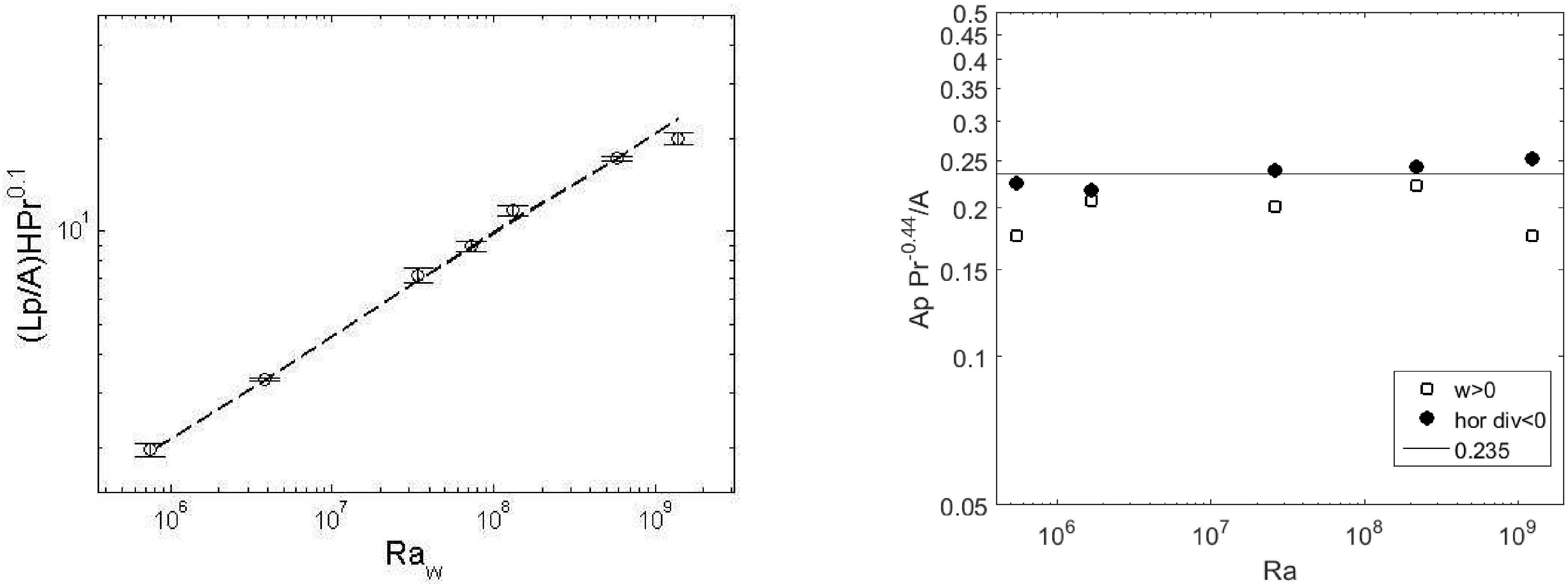
(a) w field, (b) $\overline{\nabla}_H \bullet \overline{V}$ field @ $Ra_w = 5.44 \times 10^5, Pr = 5.9$

False plumes detected by $w > 0$ near impingement regions, unlike with $\overline{\nabla}_H \bullet \overline{V} < 0$



(a) w field, (b) $\overline{\nabla}_H \bullet \overline{V}$ field @ $Ra_w = 1.24 \times 10^9, Pr = 5.1$

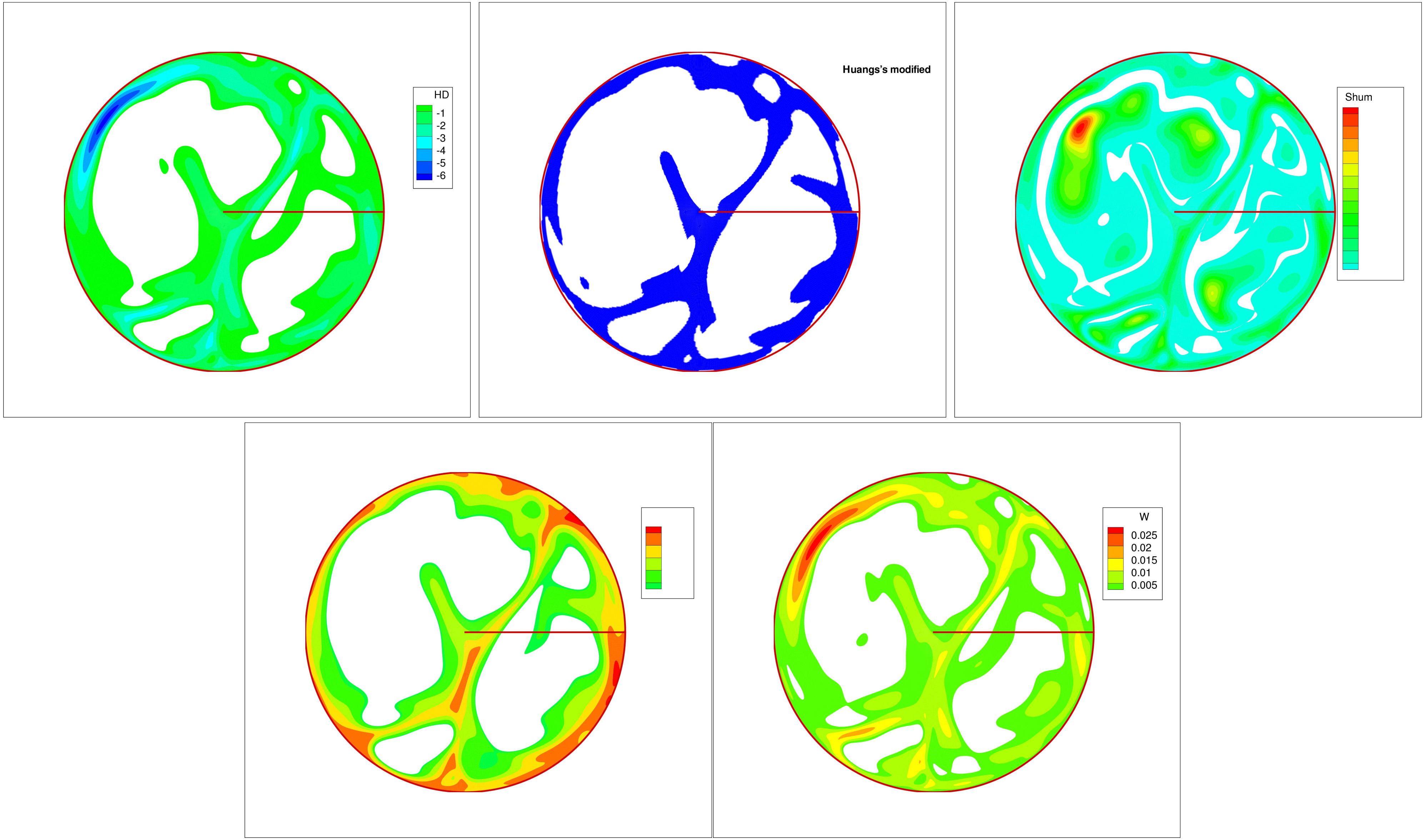
More plumes, with more details using $\overline{\nabla}_H \bullet \overline{V} < 0$



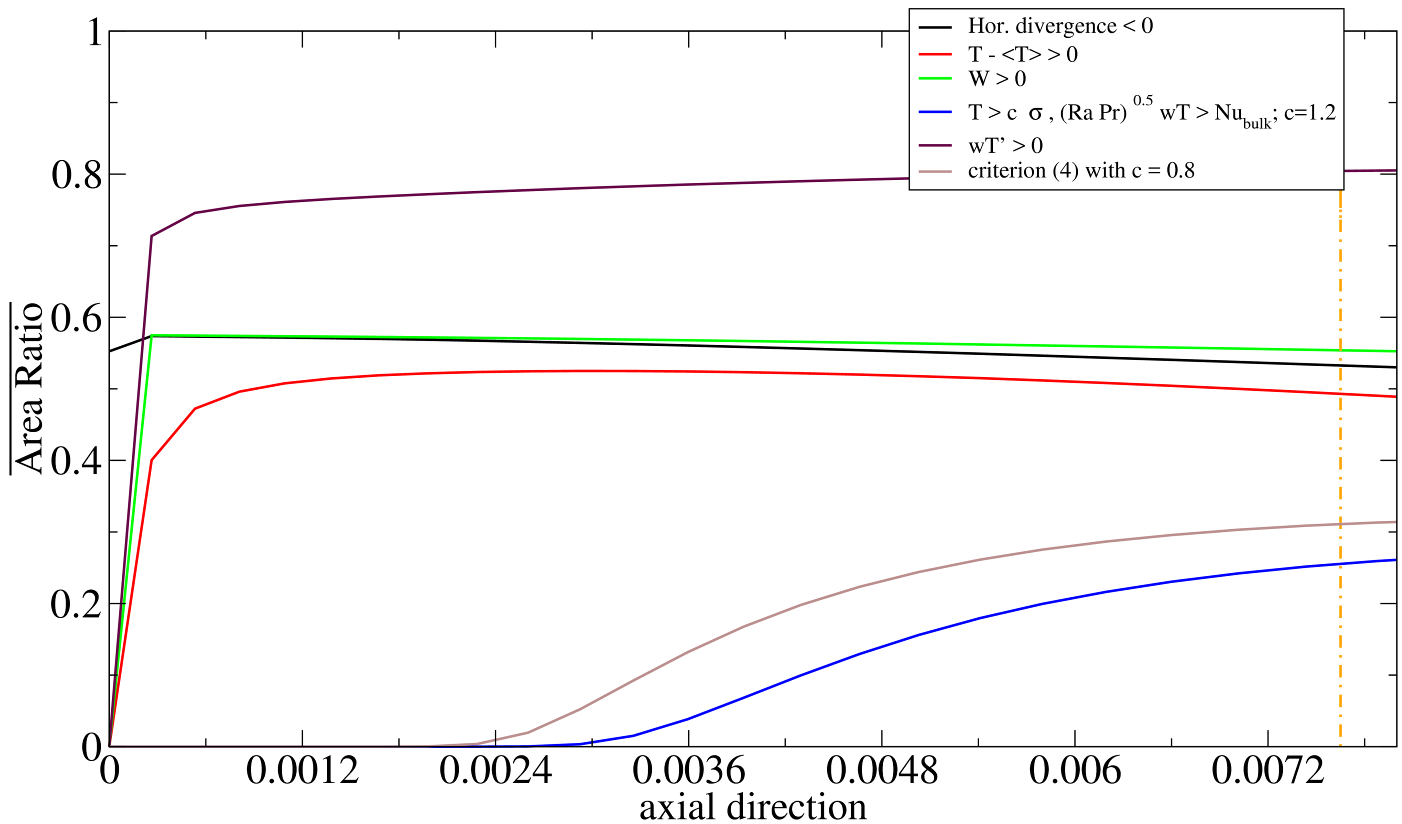
(a) Plume length vs Ra_w from $\overline{\nabla}_H.\overline{V}$ criterion; (b) Plume area ratio vs Ra_w.

- Plume lengths match with $L_p/(A/H) = Ra_w^{1/3}/(C_1 Pr^{n_1})$ (Puthenveettil et al, JFM, 685,2011)
- Plume area ratios match with $Ap/A = C_2 Pr^{0.44}$ obtained from $A_p \sim 2\delta_v L_p$, where $\delta_v = (C_1/2)^{2/5} Z_w Pr^{0.44}$ (Puthenveettil et al, JFM, 685,2011)

Total length and area from $\overline{\nabla}_H \bullet \overline{V} < 0$ match theory.

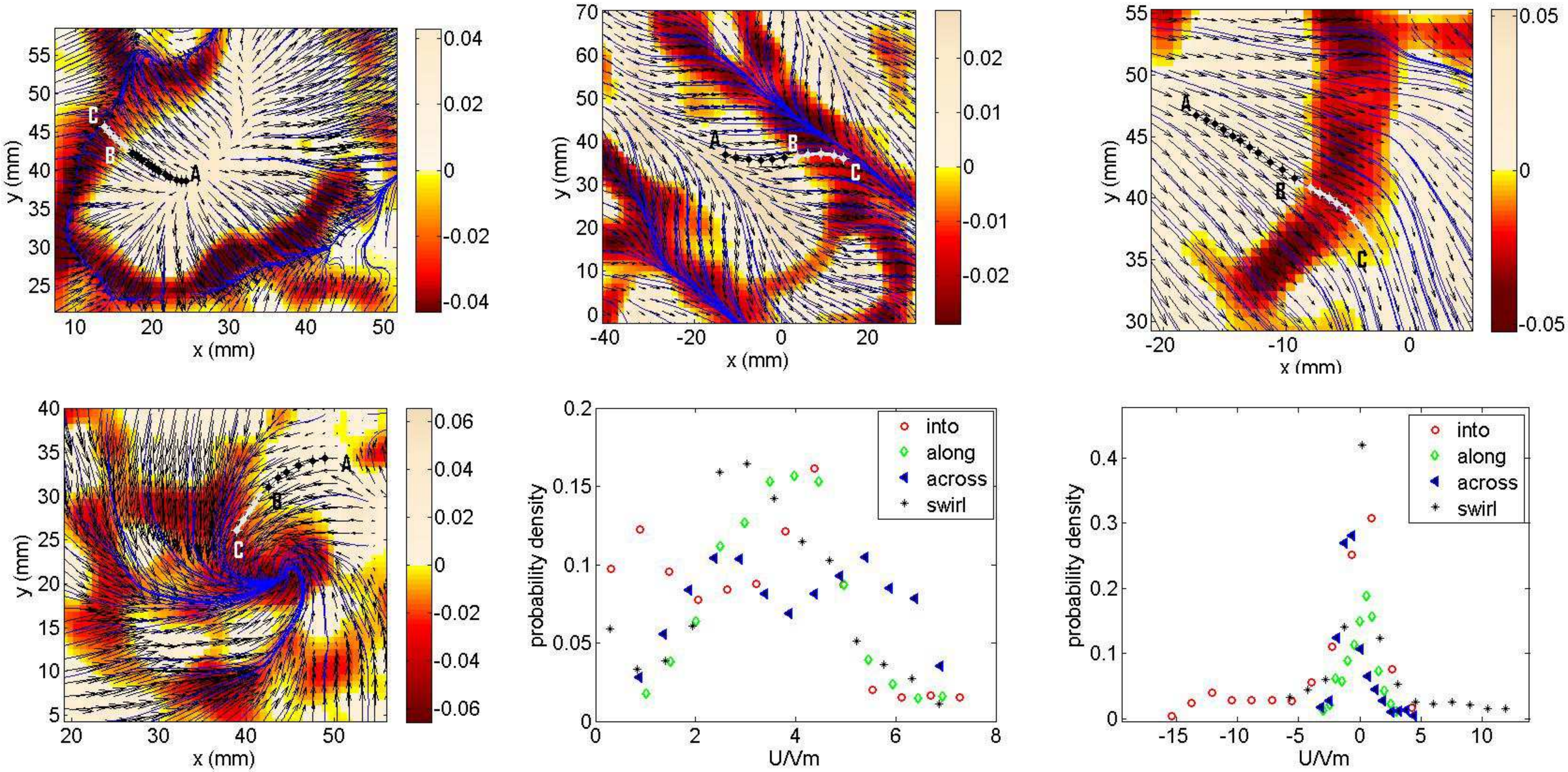


Comparison of different criteria @ $Ra = 2 \times 10^8$, $Pr = 1$ (a) $\overline{\nabla}_H \bullet \overline{V} < 0$; (b) $T' > c\sqrt{\overline{T'^2}} + wT > cNu$(Huang et al. PRL, 111, 2013); (c) $wT' > 0$; (d) $T' > 0$; (e) $w > 0$.



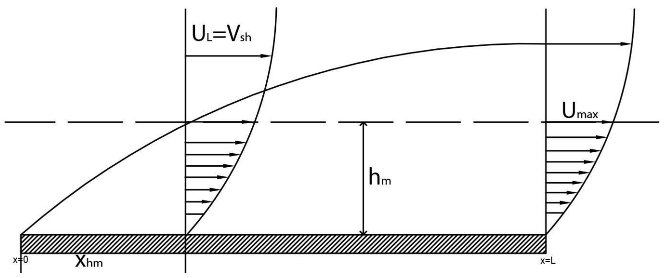
Plume area ratio with height from different criteria

$\overline{\nabla}_H \bullet \overline{V} < 0$ closest to $w > 0$ in the absence of large scale flow/impingement.

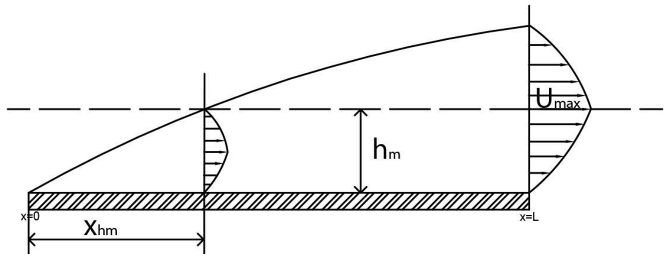


(a) Into the plumes $Ra_w = 1.32 \times 10^8$ (b) Along the plumes $Ra_w = 3.84 \times 10^6$ (c) Across the plumes $Ra_w = 1.32 \times 10^8$ (d) Swirl $Ra_w = 1.32 \times 10^8$ (e) PDF of $U = \sqrt{u^2 + v^2}$ (f) PDF of w

The four patterns have different PDFs

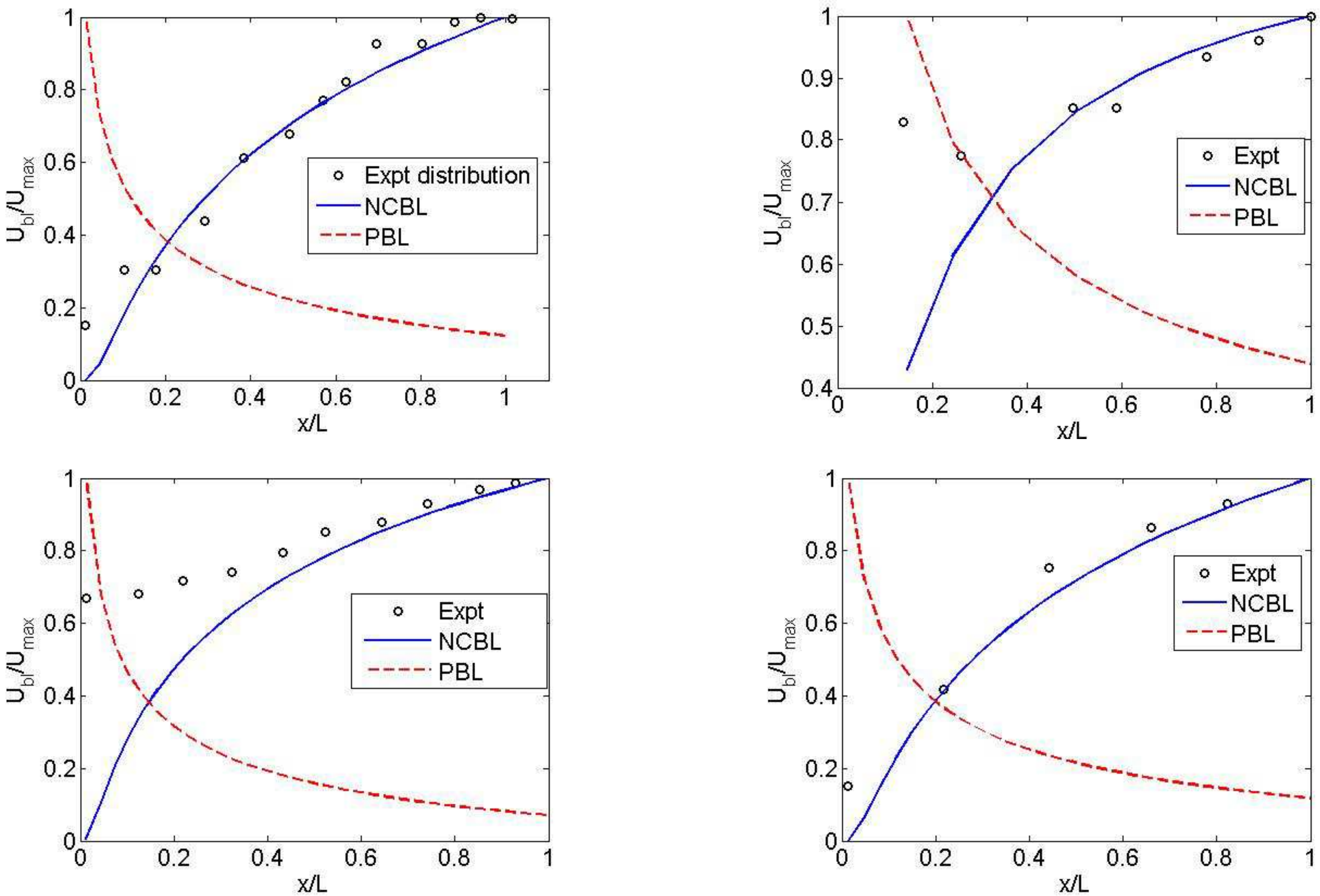


(a) Prandtl-Blasius Boundary Layer



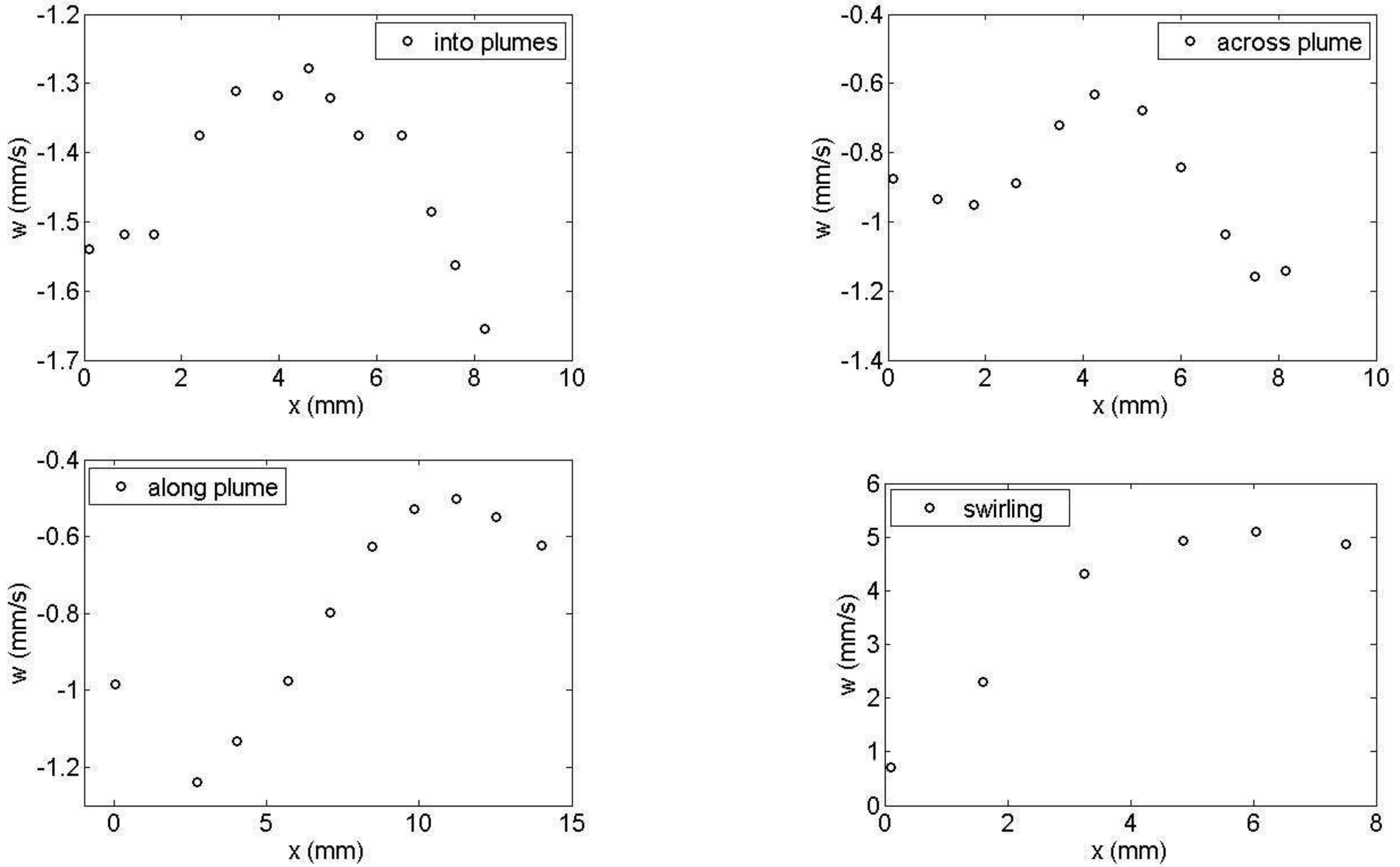
(b) Natural convection Boundary layer

- Prandtl- Blasius Boundary layers (PBBL):
  1. driven by zero pressure gradient external flow,
  2. flow detrains from boundary layer,
  3. flow decelerates horizontally along a horizontal plane.
- Natural convection boundary layers (NCBL):
  1. driven by horizontal density gradients, no external flow,
  2. flow entrains into boundary layer,
  3. flow accelerates horizontally along a horizontal plane.



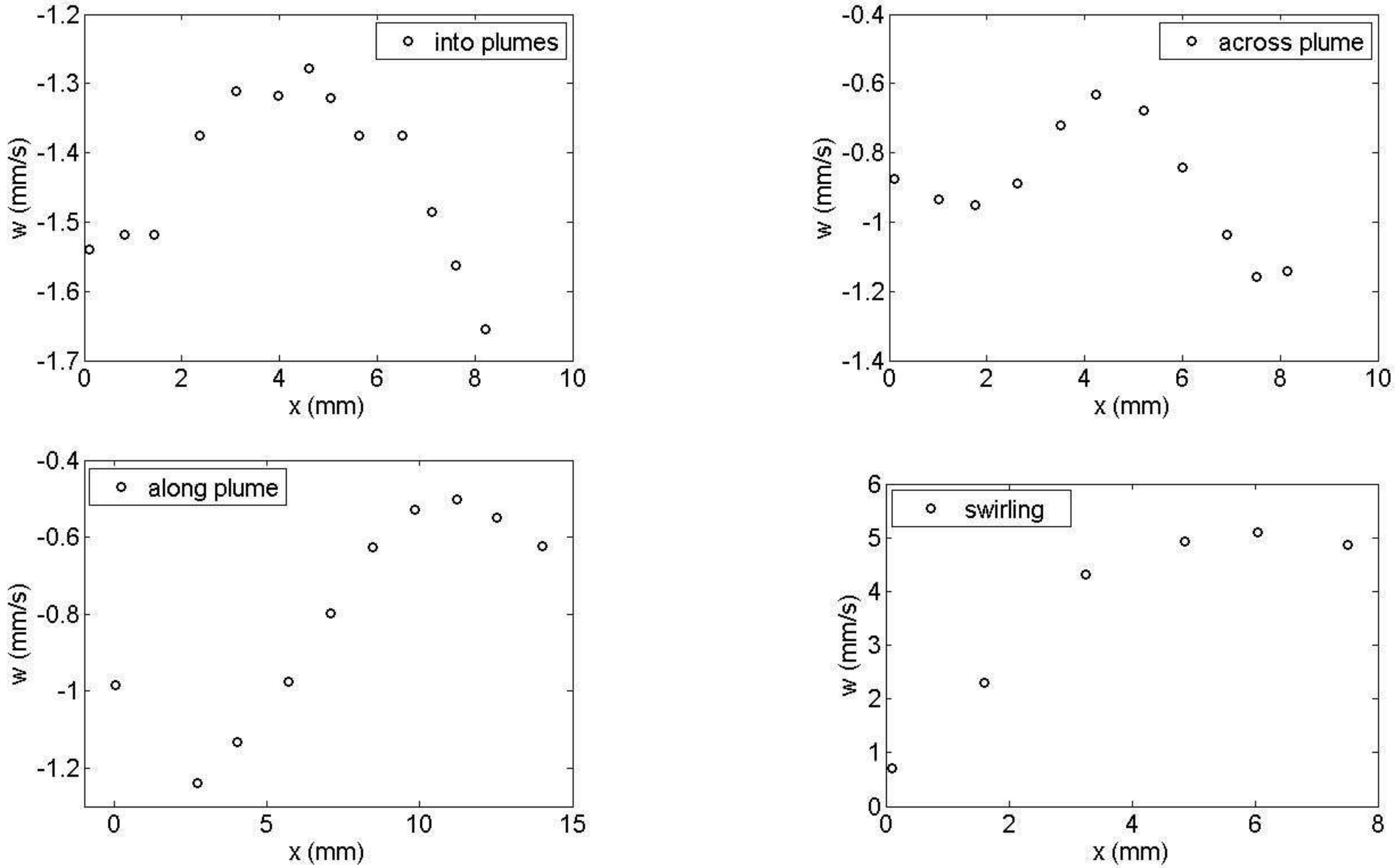
(a) Into the plumes (b) Along the plumes (c) Across the plumes (d) Swirl

- Flow accelerates horizontally in a horizontal plane: not possible in Blasius boundary layers.



(a) Into the plumes (b) Along the plumes (c) Across the plumes (d) Swirl

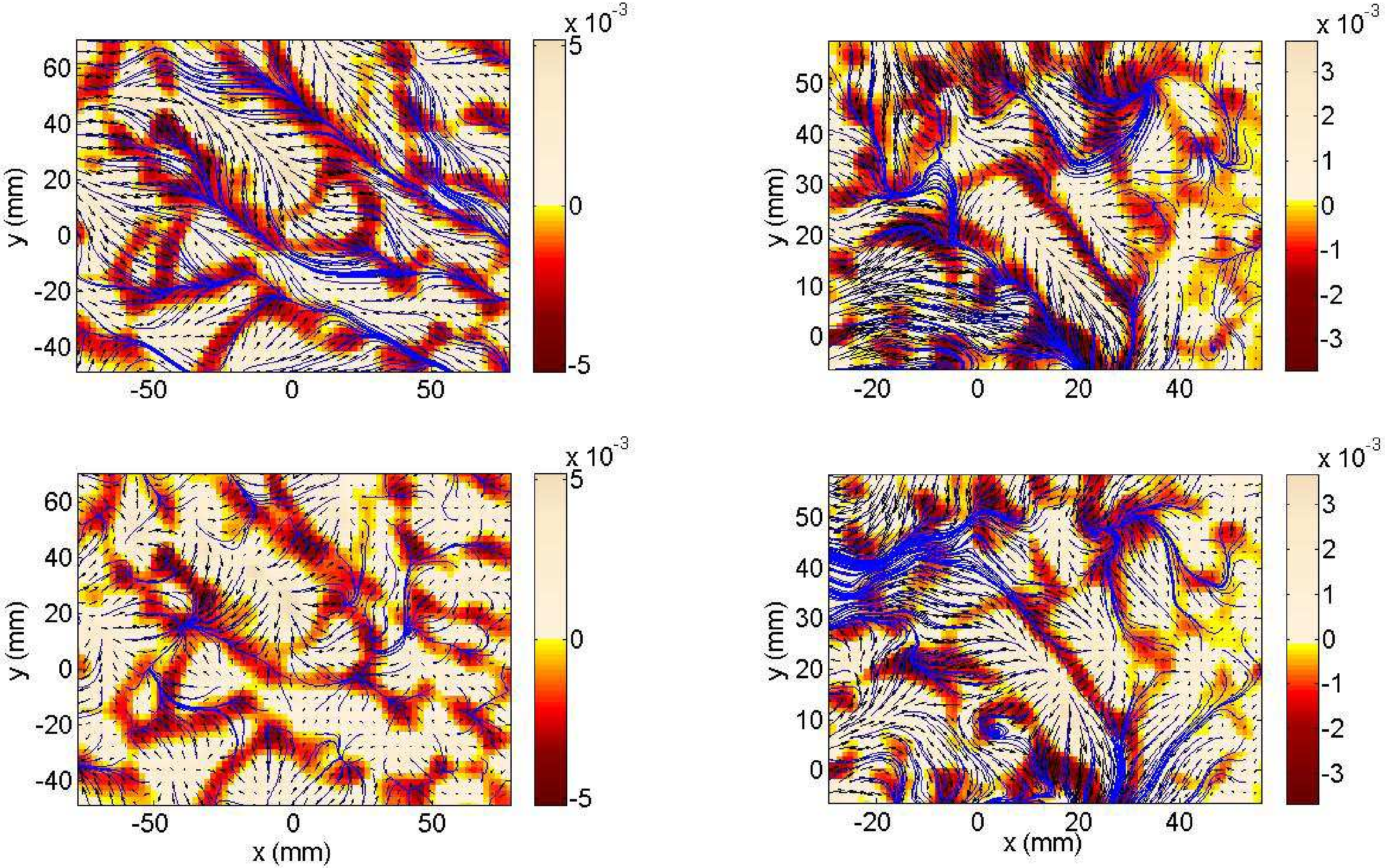
- Flow entrains into the boundary layers: not possible in Blasius boundary layers.



(a) Into the plumes (b) Along the plumes (c) Across the plumes (d) Swirl

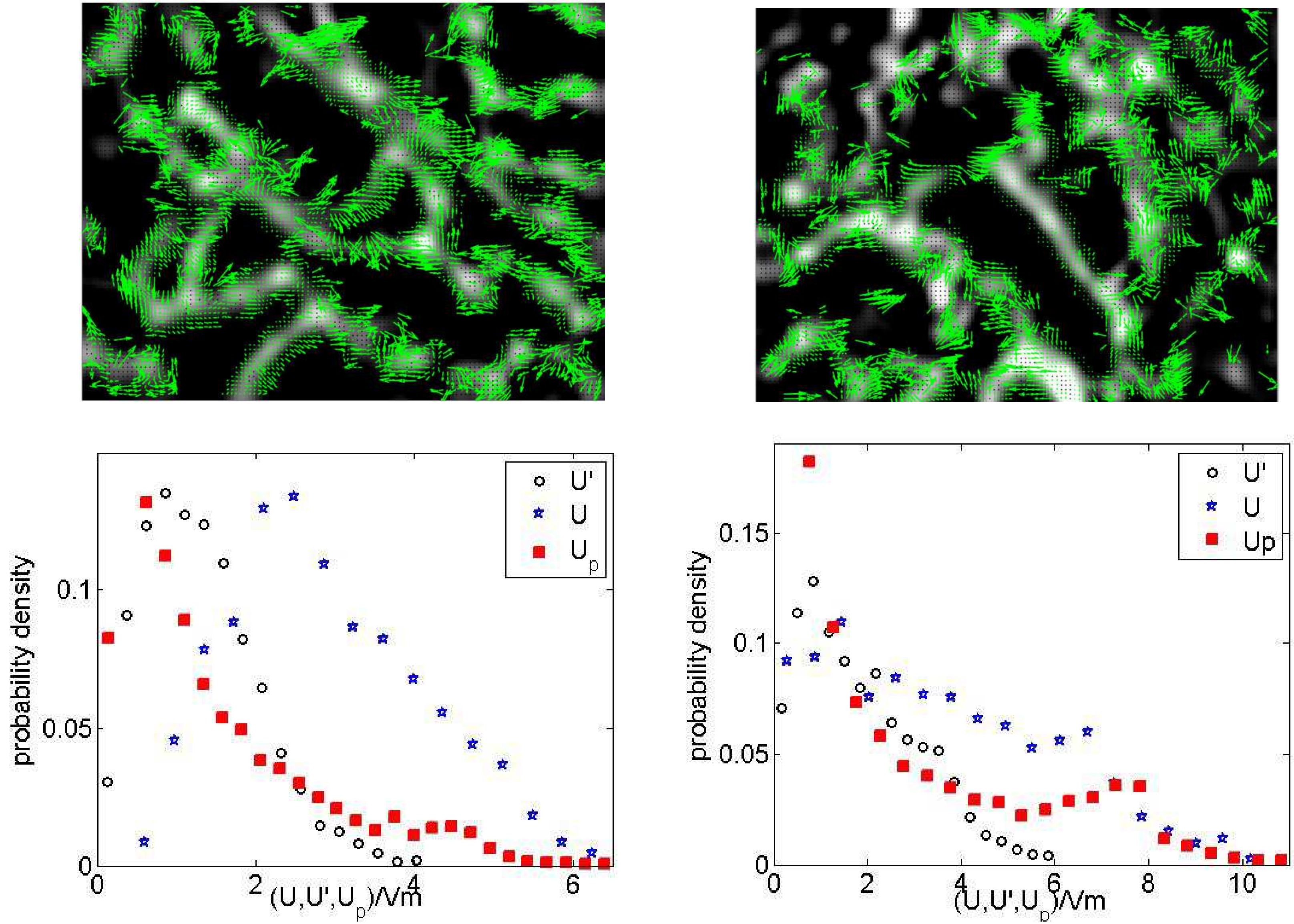
- Flow entrains into the boundary layers: not possible in Blasius boundary layers.

  The boundary layers are predominantly NCBLs affected by shear.



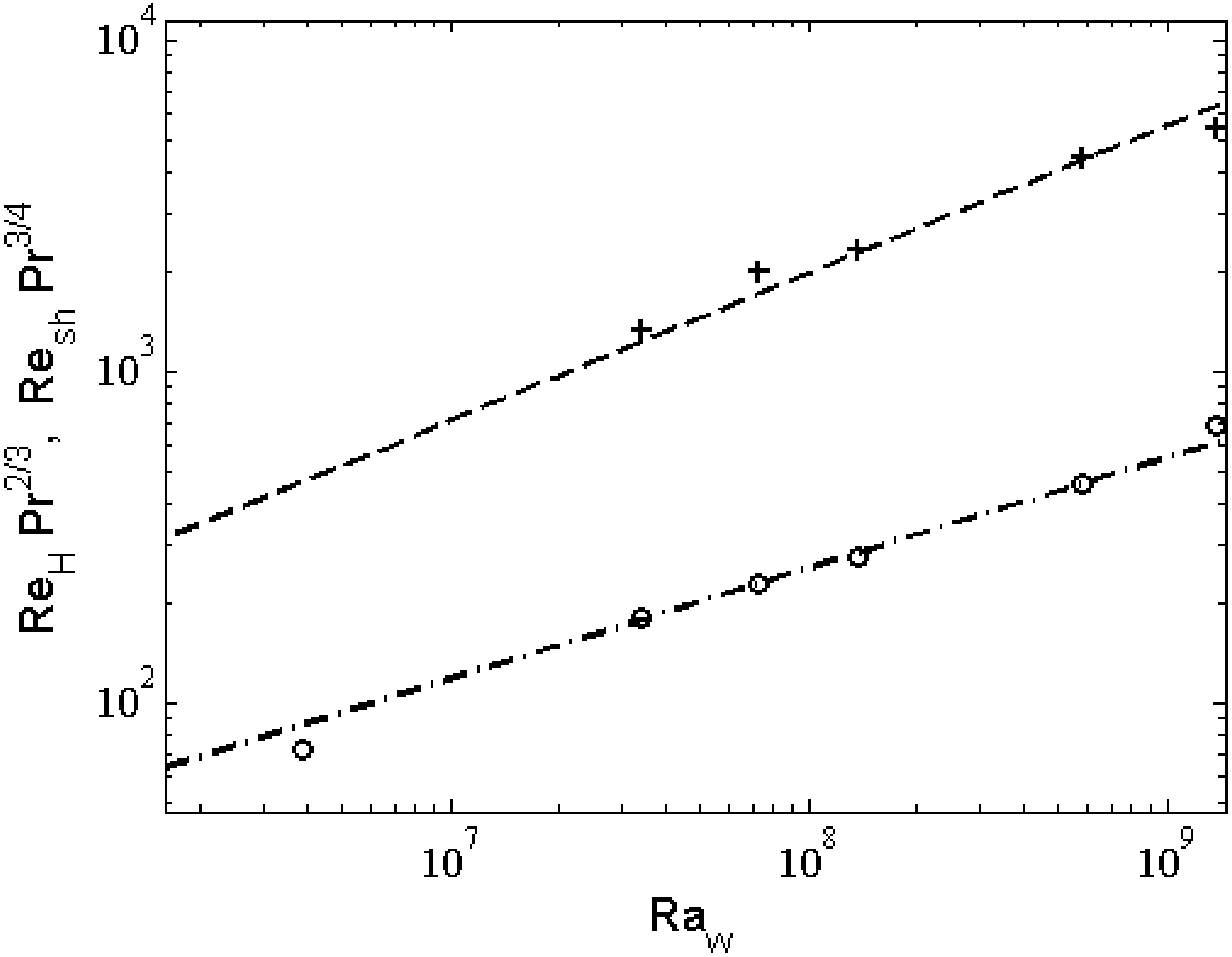
(a) & (b) Instantaneous fields at $Ra = 3.84 \times 10^6$ and $Ra_w = 1.32 \times 10^8$; (c) & (d) Fluctuating fields at the same Ra_w.

Fluctuating fields seem driven by plumes.



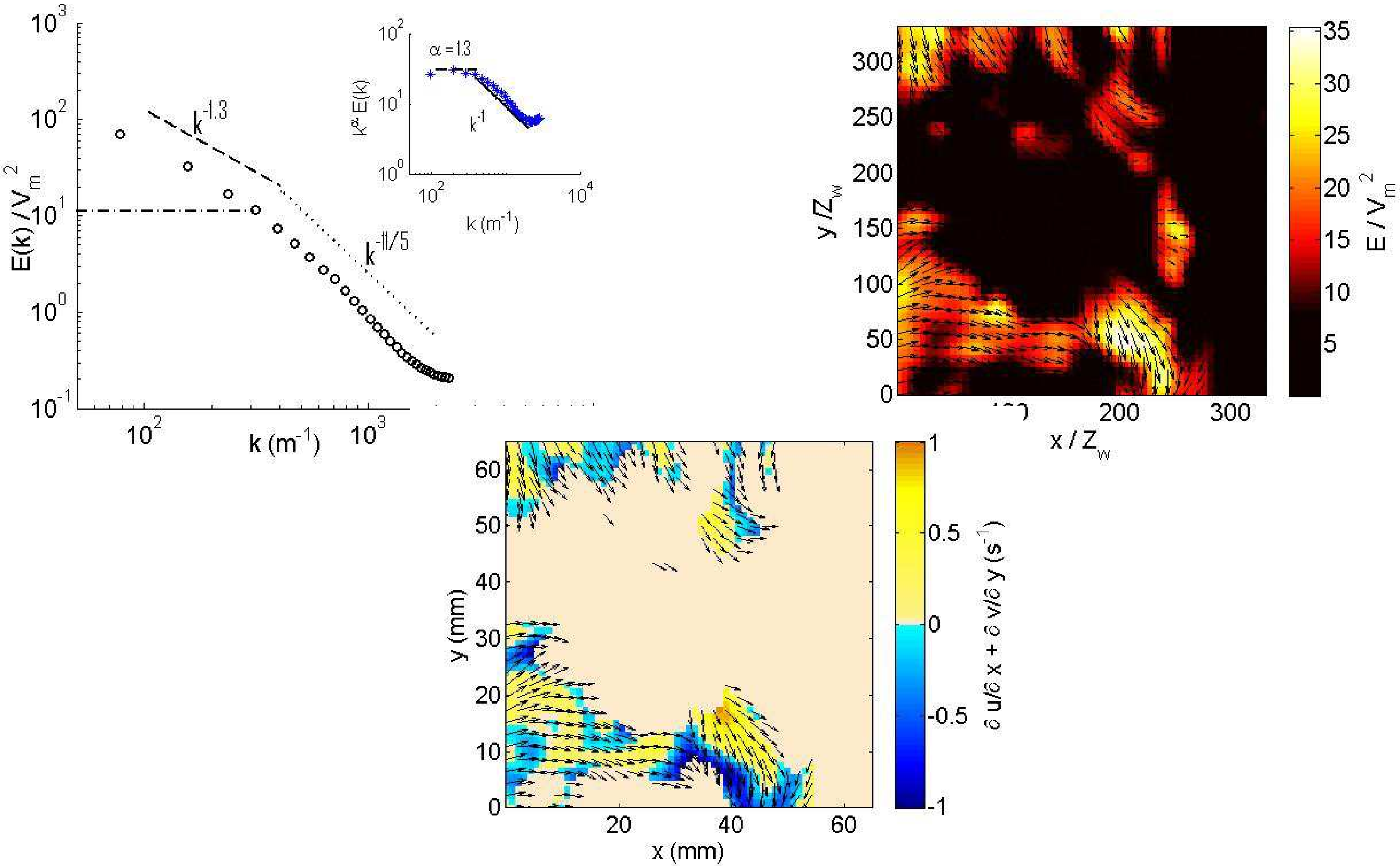
(a) & (b) Plume velocity fields at $Ra = 3.84 \times 10^6$ and $Ra_w = 1.32 \times 10^8$; (c) & (d) PDFs of fluctuating, plume and instantaneous horizontal at the same Ra_w.

PDF of plume and fluctuating velocities match.



Plume velocity PDF peaks vs Ra_w, −−; −·

The first peak is due to merging and the second peak due to shear.



(a) Choosing the $k^{-11/5}$ cut off, $Ra_w = 1 \times 10^8$ (b) Regions where k^{-1} holds (c) Regions corresponding to the second PDF of hor. velocities.

Shear predominant regions give rise to the k^{-1} scaling.

Divergence criterion separates plumes from local boundary layers, which can then be used to study the boundary layers and plumes.

Divergence criterion separates plumes from local boundary layers, which can then be used to study the boundary layers and plumes.

- DST, for funding.
- J. H. Arakeri, IISc, suggestions.
- Murali Cholemari, IITD, suggestions.

- DST, for funding.
- J. H. Arakeri, IISc, suggestions.
- Murali Cholemari, IITD, suggestions.

Thank you for your attention!