Production and energy transfer in wall bounded shear flows

E. De Angelis[1]
in collaboration with
A. Cimarelli[1], P. Schlatter[3], G. Brethouwer[3], A. Talamelli[1], C.M. Casciola[2], J. Jimenez[4]

[1]Alma Mater Studiorum, University of Bologna
[2]La Sapienza, Roma
[3]KTH Mechanics, Stockholm
[4]Universidad Politécnica de Madrid

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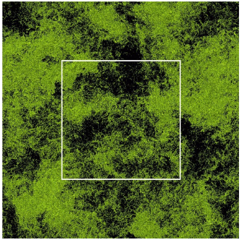
Wall-bounded flows

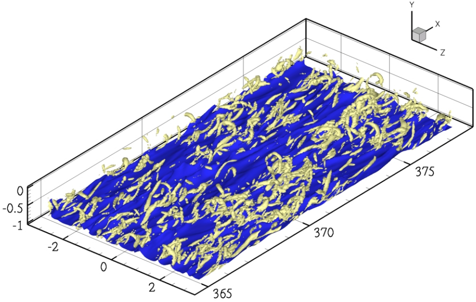
One of the most peculiar aspect of turbulence in wall bounded flows is the ability of the turbulent fluctuations to regenerate themselves forming self-sustained processes.

Isotropic turbulence
(External forcing)

Inhomogeneous anisotropic turbulence
(Embedded production)



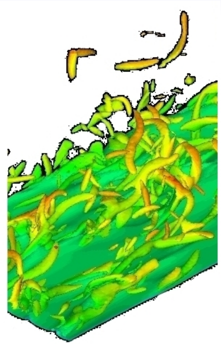
Kaneda et al. JoT, 2006.



The production of turbulent fluctuations is embedded in the system rather than being provided by an external agent.

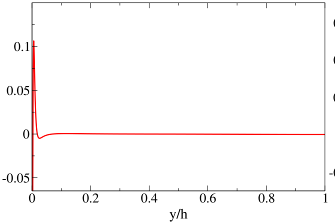
Near-wall cycle

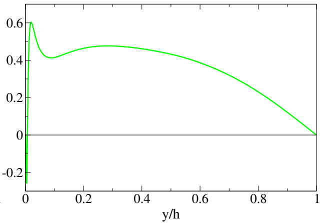
- Well-defined coherent motion;
- Cyclic regeneration mechanisms;
- At low Re the turbulent motion is sustained by energy coming from the near-wall cycle;



TKE balance:

$$\frac{d\phi}{dy} = s(y) = \pi(y) - \epsilon(y)$$



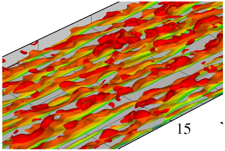


S. Hoyas and J. Jimenez: Channel flow $Re_\tau = 2003$

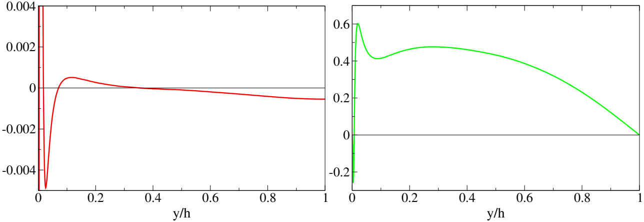
Outer cycle

Turbulent production is active also in the overlap layer

- Production exceeds dissipation violating the equilibrium assumptions ;
- Large Reynolds number state dominated by the overlap layer dynamics;



$$\frac{d\phi}{dy} = s(y) = \pi(y) - \epsilon(y)$$



S. Hoyas and J. Jimenez: Channel flow $Re_\tau = 2003$

A multidimensional approach to wall-turbulence

Second order structure function: $\langle \delta u^2 \rangle = \langle \delta u_i \delta u_i \rangle (\mathbf{r}, \mathbf{X_c})$

- $\delta u_i = u_i(x_s + r_s) - u_i(x_s)$: fluctuating velocity increments
- $\mathbf{r} = (r_x, r_y, r_z)$: separation vector

Analysis of the energy fluxes in the augmented space (r_x, r_y, r_z, Y_c),

$$\frac{\partial \langle \delta u^2 \delta u_i \rangle}{\partial r_i} + \frac{\partial \langle \delta u^2 \delta U \rangle}{\partial r_x} - 2\nu \frac{\partial}{\partial r_i} \left(\frac{\partial \langle \delta u^2 \rangle}{\partial r_i} \right) +$$

$$\frac{\partial \langle v^* \delta u^2 \rangle}{\partial Y_c} + \frac{2}{\rho} \frac{\partial \langle \delta p \delta v \rangle}{\partial Y_c} - \frac{\partial}{\partial Y_c} \left(\frac{\partial \langle \delta u^2 \rangle}{\partial Y_c} \right) = - \left(2 \langle \delta u \delta v \rangle \left(\frac{dU}{dy} \right)^* - 4 \langle \epsilon^* \rangle \right)$$

$\nabla \cdot$ (Energy flux across scales + Spatial energy flux)= Sink or source of energy

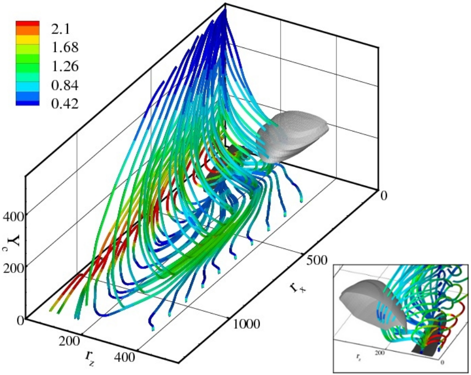
Re_τ	L_x	L_y	L_z	Δx^+	Δz^+
550	$8\pi h$	$2h$	$4\pi h$	13	6
1000	$8\pi h$	$2h$	$3\pi h$	9.8	3.7
1500	$12\pi h$	$2h$	$10.5h$	9.2	4.5

Analysis of DNS data of a turbulent channel flow

Small-scale energy sourcing and reverse energy transfer

The stationary Kolmogorov equation can be written also

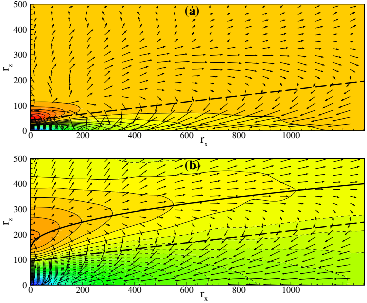
$$\nabla_4 \cdot \mathbf{\Phi}(r_x, r_y, r_z, Y_c) = \xi(r_x, r_y, r_z, Y_c)\,, \qquad (r_y = 0)$$



Cimarelli, De Angelis, Casciola, JFM, 2013.

Small-scale energy sourcing and reverse energy transfer

Looking at the projections of the reduced inertial hyper-flux and energy source isolines in the $Y_c = 20$ and $Y_c = 110$ planes, respectively



The dashed lines in (a) and (b), $r_z = 0.12 r_x + 9(Y_c)^{1/2}$, is the boundary of the energy sink. The solid line in (b), $r_z \propto r_x^{1/2}$, is the locus of the maxima of ξ.

Cimarelli, De Angelis, Casciola, JFM, 2013.

Open questions

- What about the Re-dependence?

$\Rightarrow$ DNS of turbulent channel at $Re_\tau = 550, 1000, 1500$ have been analyzed in collaboration with the KTH's group guided by P. Schlatter

- What about $r_y \neq 0$?

$\Rightarrow$ The analysis performed up to now have considered the behavior of energy in the (r_x, r_z, Y_c)-space with $r_y = 0$.
$\Rightarrow$ Space of scales is a homogeneous concept but $r_y \neq 0$ takes into account inhomogeneous data!!
$\Rightarrow$ I will present some results done within the Multiflow program in Madrid

Scale-energy source and transfer

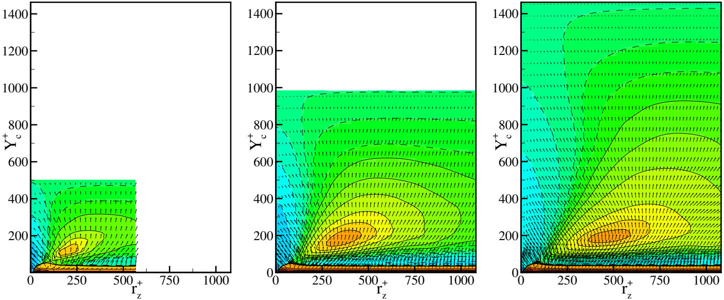


Figure: Energy source $\xi^+(Y_c^+, r^+) = -2\langle\delta u \delta v\rangle\,(dU/dy)^* - 4\langle\epsilon^*\rangle$ contours and fluxes Φ in the $(r_x = 0, r_y = 0)$-plane. $Re_\tau = 550$, $Re_\tau = 1000$ and $Re_\tau = 1500$ from left to right.

Two peaks of energy source appear

- Buffer layer: $\xi^+_{max} = 0.72, 0.73, 0.74$ **DSR** (Driving Scale Range)
- Overlap layer: $\xi^+_{max} = 0.095$, **OSR** (Outer Scale Range)

⇒ The field of fluxes take origin from the **DSR** sustaining the whole turbulence.

⇒ The **OSR** increases with *Re* and modifies the topology of the field of fluxes

Near-wall cycle

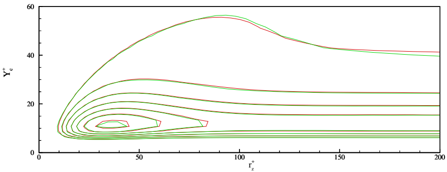


Figure: Iso-contours of ξ^+ in the $(r_x = 0, r_y = 0)$-plane for the three *Re* considered.

Maximum of ξ^+ in the buffer is at scales $r_z^+ = 35$ and $r_x^+ < 200$

$\Downarrow$

Strongly related to the **near-wall cycle** and to the **streamwise vortices**

The driving scale range, DSR;

- Reynolds-invariant location in viscous units, $(r_x^+ < 200, r_z^+ = 40, Y_c^+ = 12)$;
- Within the buffer the spanwise scales of the source are indipendent of the wall-distance;
- The source intensity varies mildly, $\xi^+_{max} = 0.72, 0.73, 0.74$;

Outer cycle - I

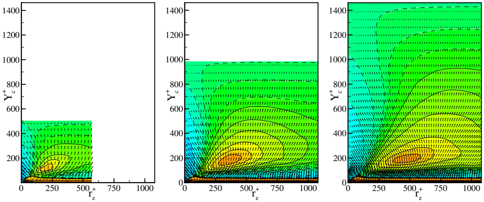


Figure: Energy source ξ^+ contours and fluxes Φ in the $(r_x = 0, r_y = 0)$-plane. $Re_\tau = 550$, $Re_\tau = 1000$ and $Re_\tau = 1500$ from left to right.

Outer cycle features

- Outer-scaling of the OSR: $\xi^+ = 0.095$ at $r_z = 0.34$ independent on Re;

Outer cycle - II

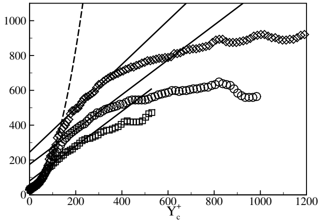


Figure: Locus of the energy source ξ in the $(r_x = 0, r_y = 0)$-plane.

Outer cycle features

- Outer-scaling of the OSR: $\xi^+ = 0.095$ at $r_z = 0.34$ independent on Re;
- The spanwise scales increase linearly: $r_z \propto Y_c$;

Outer cycle - III

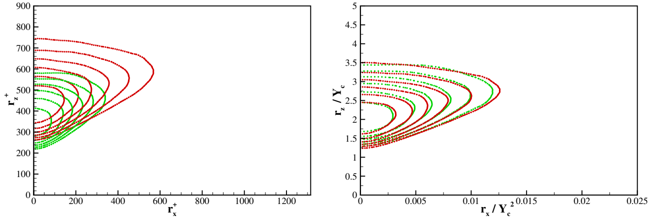


Figure: Scaling of the source for different distances from the wall in the (r_x, r_z)-space for the $Re_\tau = 1500$ case. Left inner scaling and right outer scaling.

Outer cycle features

- Outer-scaling of the OSR: $\xi^+ = 0.095$ at $r_z = 0.34$ independent on Re;
- The spanwise scales increase linearly: $r_z \propto Y_c$;
- The streamwise scales increase quadratically $r_x \propto (Y_c)^2$ hence $r_z \propto (r_x)^{1/2}$;

Outer cycle - IV

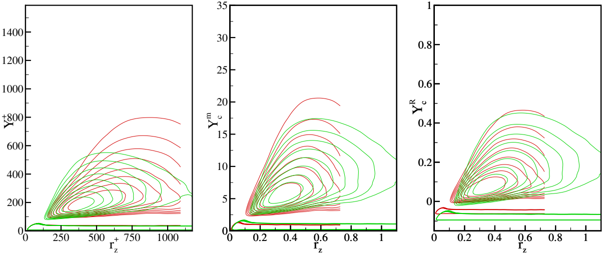


Figure: ξ^+ in the $(r_x = 0, r_y = 0)$-plane for $Re_\tau = 1000$ (green) and $Re_\tau = 1500$ (red).

Outer cycle features

- Outer-scaling of the OSR: $\xi^+ = 0.095$ at $r_z = 0.34$ independent on Re;
- The spanwise scales increase linearly: $r_z \propto Y_c$;
- The streamwise scales increase quadratically $r_x \propto (Y_c)^2$ hence $r_z \propto (r_x)^{1/2}$;
- Mixed scaling of the wall-distance $(100 < Y_c^+ < 0.2Re_\tau)$:

$$Y_c^m = \sqrt{Y_c Y_c^+} \qquad Y_c^R = Y_c - \eta^+/Re_\tau \qquad \text{with} \qquad \eta^+ = 100$$

Outer cycle - V

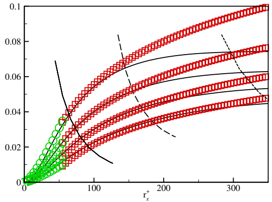


Figure: Scale-space production scaling for the $Re_\tau = 1500$.

Outer cycle features

- Outer-scaling of the OSR: $\xi^+ = 0.095$ at $r_z = 0.34$ independent on Re;
- The spanwise scales increase linearly: $r_z \propto Y_c$;
- The streamwise scales increase quadratically $r_x \propto (Y_c)^2$ hence $r_z \propto (r_x)^{1/2}$;
- Mixed scaling of the wall-distance $(100 < Y_c^+ < 0.2 Re_\tau)$:

$$Y_c^m = \sqrt{Y_c Y_c^+} \qquad Y_c^R = Y_c - \eta^+/Re_\tau \qquad \text{with} \qquad \eta^+ = 100$$

- Logarithmic behavior of the intensity for large scales (k^{-1}-law),

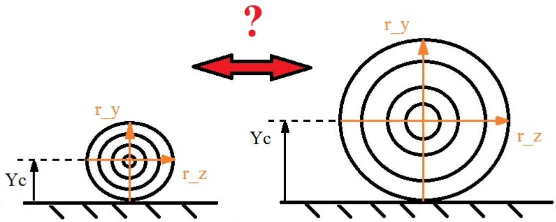
$$\langle \delta u \delta v \rangle (dU/dy) \sim \log(r/y)/(\kappa y)$$

Analysis of the $r_y \neq 0$ behaviour

- We can describe how attached and detached scales are generated.
- What is their multidimensional behavior?

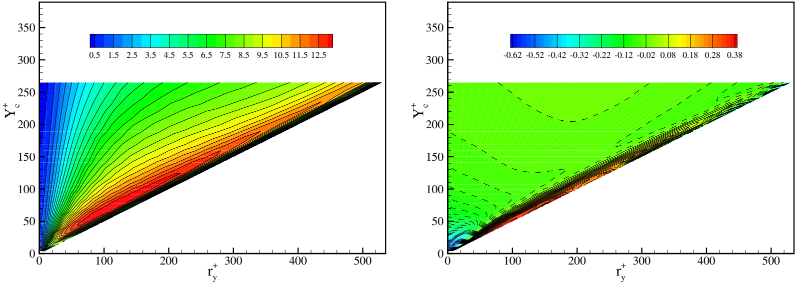
$\Downarrow$

Analysis of the (r_y, r_z, Y_c)-space!



How a given turbulent structure at a given distance from the wall and for given spanwise and wall-normal length is generated?

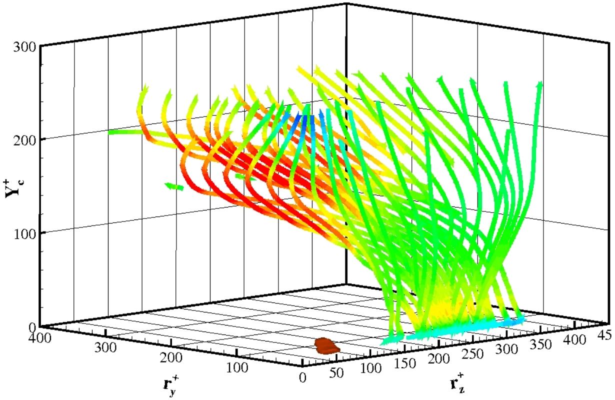
Channel flow $Re_\tau = 550$ - I



Scale-energy, δu^2, (left) and energy source/sink, ξ, (right) in the $(r_x = r_z = 0)$-plane.

- Maximum of scale-energy associated with attached scales, $r_y \sim 2Y_c$;
- These scales are also those responsible for most of the local production;

Channel flow $Re_\tau = 550$ - II



Scale-energy paths, $\mathbf{\Phi}$, in the $(r_x = 0)$-space.

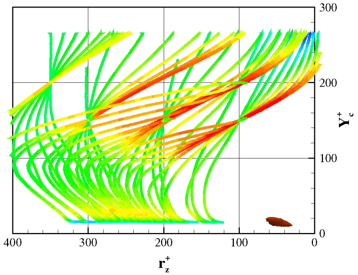
- Peak of energy source at $(r_y^+, r_z^+, Y_c^+) = (7, 40, 14)$;
- Single singolarity point for the fluxes;
- Spiraling behavior, simultaneous presence of forward and reverse cascades:

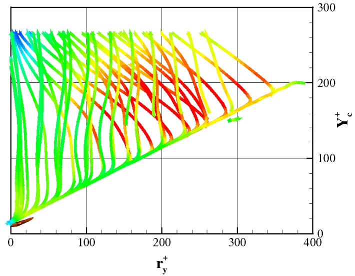
Channel flow $Re_\tau = 550$ - III

- From the near-wall source the fluxes intercept larger and taller scales while ascending to the bulk;
- Reverse cascade: linear increase with wall-distance of the scales involved:

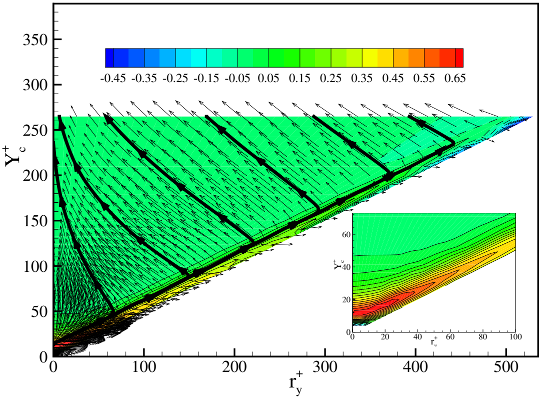
$$r_y^+ = 2Y_c^+$$
$$r_z^+ = \Delta z_{nw}^+ + 1/2 r_y^+ \propto Y_c^+$$

- As soon as the $r_y^+ = 2Y_c^+$-plane is left, the fluxes converge to the small dissipative scales again ascending to the bulk, Forward cascade;



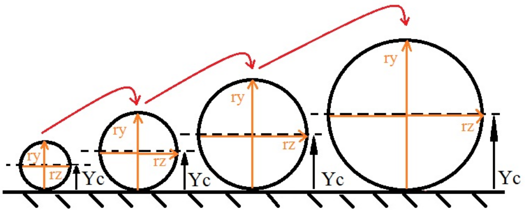


Channel flow $Re_\tau = 550$ - IV



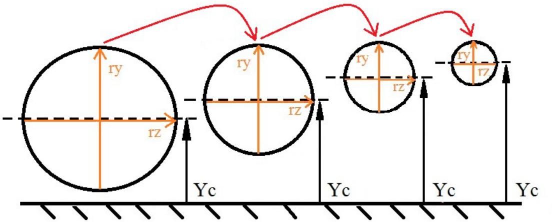
Scale-energy paths, $\mathbf{\Phi}$, in the $(r_x^+ = 0, r_z^+ = 40)$-space.

Attached scales



- Attached scales ($r_y \sim 2Y_c$) are involved in a reverse cascade process starting from the wall and propagating to the bulk;
- At a given distance from the wall, the attached scale is fed by the smaller attached scales immediately below and contributes to sustainment of the structures above;
- Among the attached scales for the different wall-distances the energy source is continuously active;

Detached scales



- Detached scales ($r_y \leq 2Y_c$) are instead involved in a forward cascade process propagating to the bulk;
- At a given distance from the wall, a given detached scalee is fed by larger detached scales immediately below;
- This detached scale in turn feeds smaller structures further away from the wall up to dissipation;

Conclusions

The multidimensional description of turbulence given by the Kolmogorov equation appears to be an useful statistical tool for the study of the overlap layer dynamics.

We observe

- A well defined second peak of energy source in the overlap layer (**OSR**);
- The **OSR** highlights different features attached to the wall;

From these observations we conjecture also that

- The activity of the **OSR** influences the near-wall dynamics through a modification of the topology of the energy fluxes emerging from the buffer layer (mixed inner/outer scaling);
- The large Reynolds number state might be dominated by the overlap layer production but without the appearence of a new singularity point in this region.

Conclusions - II

From the data at $r_y \neq 0$ we conjecture also that

- Two cascade mechanisms are found to coexist in wall-turbulence they are superimposed to a spatial flux. One involving scales attached to the wall and another characterizing the detached motion.
- At a given distance from the wall, Y_c, the attached motion is fed by a hierarchy of smaller attached scales located closer to the wall.
- The energy source associated to the attached scales is also strong enough to initialize at each distance from the wall a direct forward cascade toward smaller detached scales.
- This forward cascade represents the Y_c-distributed link of the production processes in the attached motion with the dissipation at the smallest scales.