On Large Scale Motions in Wall Bounded Turbulent Flows

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INTRODUCTION
WALL BOUNDED TURBULENCE
Buffer layer quasi-streamwise vortices

******5 decades of research***; well established characteristics.

*Contribute to more than 80% to the Reynolds shear stress.

*Universal, the streamwise vorticity within the QSV's depends slightly on Re number.

* ***Huge literature*** (see Tardu, Wiley, 2014)

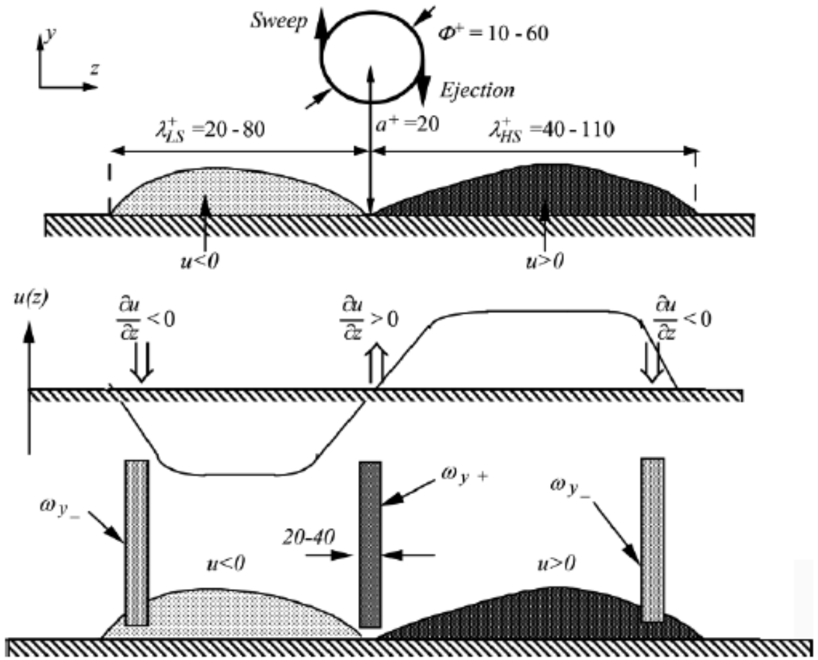
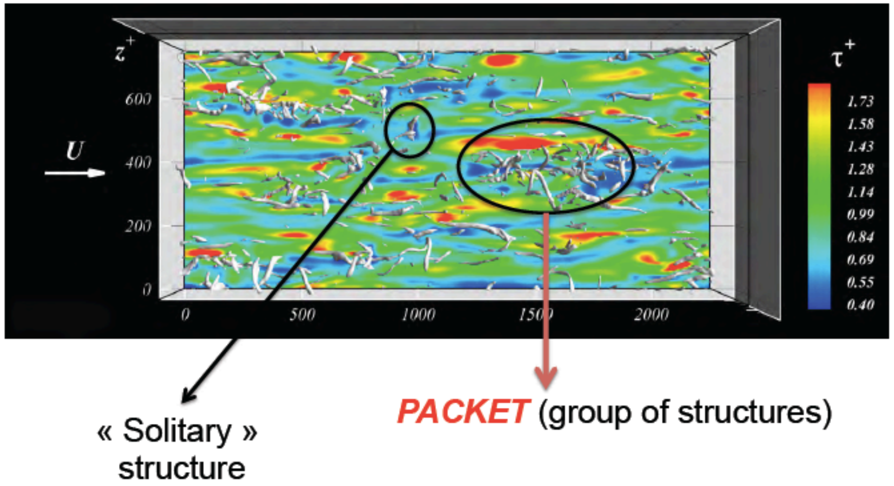


Figure 5.1. *Structural elements associated with quasi-streamwise vortices in the inner sublayer*



Large and very large scale passive motions

Buffer layer (active) structures contribute mostly to the Reynolds shear stress ➔ Independence via *R*e : They contribute In majority to the longitudinal and spanwise turbulent intensities *(but*, the passive structures play an important role at large (enough) Reynolds numbers).

Marusic's group, Adrian's group, Jiménez group, Tardu (1995, 2001)….

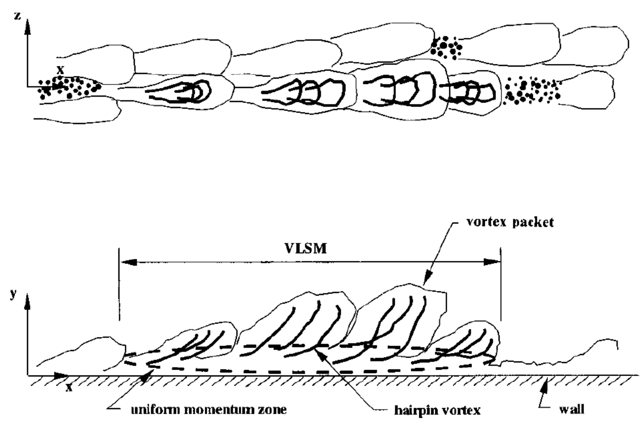
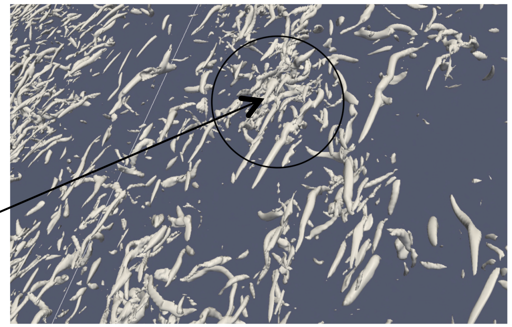
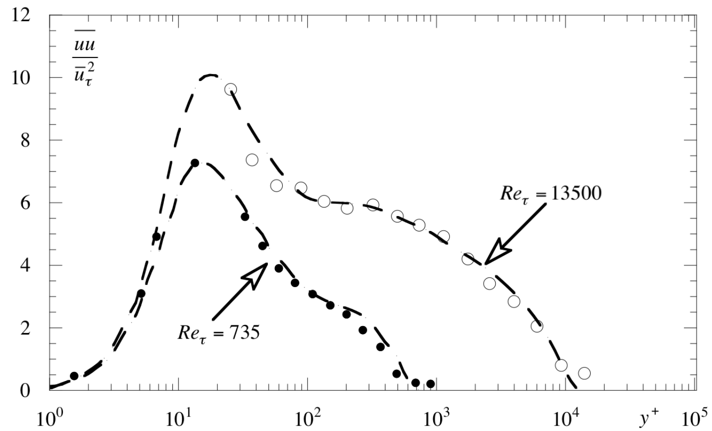


FIG. 7. The conceptual model of the process that creates very large-scale motions. Hairpins align coherently in groups to form long packets, and packets align coherently to form very large-scale motions.





AIM

- *Review of some large-scale effects in the wall turbulence*
- *CLUSTERS OF ACTIVE EDDIES*
- *➔ Phenomenology*
- *➔ MODELLING*

DNS

*Large computational domains as in (Hoyas, Jiménez 2006)

** NS with ***Dispersion Relation Preserving spatial schemes***, See Bauer, Tardu and Doche, Comp. Fluids 2014. Similar to compact schemes but 20% more rapid. See also Tardu& Bauer, Comp. Fluids, 2017, Tardu IJHFF, 2017, Tardu PoF, 2017…

ALL THE QUANTITIES ARE SCALED BY THE INNER VARIABLES, viscosity and wall shear velocity, HEREAFTER

Re_τ	Re_τ actual	Resolution ($N_x x N_y x N_z$)	Δx^+	Δy^+	Δz^+	l_x/h	l_z/h
180	178	771x129x387	8.80	0.49 (0.31η) 5.59 (1.52 η)	5.84	12π	4 π
395	396	1691x283x849	8.81	0.48 (0.33η) 5.57 (1.26η)	5.85	12π	4 π
590	588	1651x423x1113	8.98	0.48 (0.34η) 5.56 (1.15η)	5.00	8 π	3 π
1100	1104	3079x789x2075	8.98	0.48(0.34η) 5.55 (0.98η)	5.00	8 π	3 π

Simulations parameters in the streamwise, wall normal and spanwise directions (x, y, z). Both smallest (first line) and largest (second line) grid spacing are given for wall normal direction. The number in parenthesis is the wall-normal grid spacing scaled by Kolmogorov length η.

$Re_\tau = \frac{\bar{u}_\tau h}{\nu}$; Shear velocity $\bar{u}_\tau = \sqrt{\bar{\tau}/\rho}$; $\bar{\tau}$: wall shear stress ; $^+$: *Scaled by* $\bar{u}_\tau$ and viscosity ν

Large-Scale Motions

- A Reynolds number dependence of any quantity q, scaled with inner variables, i.e. shear velocity $\overline{u}_\tau = \sqrt{\tau_w / \rho}$ and viscosity ν (q^+) necessarily imply the impact of large-scales

  - ***TOWNSEND ATTACHED EDDY CONCEPT***

$$\overline{u'^2} = -A_{11} \ln(\frac{y}{L_0}) + B_{11}$$

$$\overline{v'^2} = B_{22}$$

$$\overline{u'v'} = B_{12}$$

$$\overline{w'^2} = -A_{33} \ln(\frac{y}{L_0}) + B_{33}$$

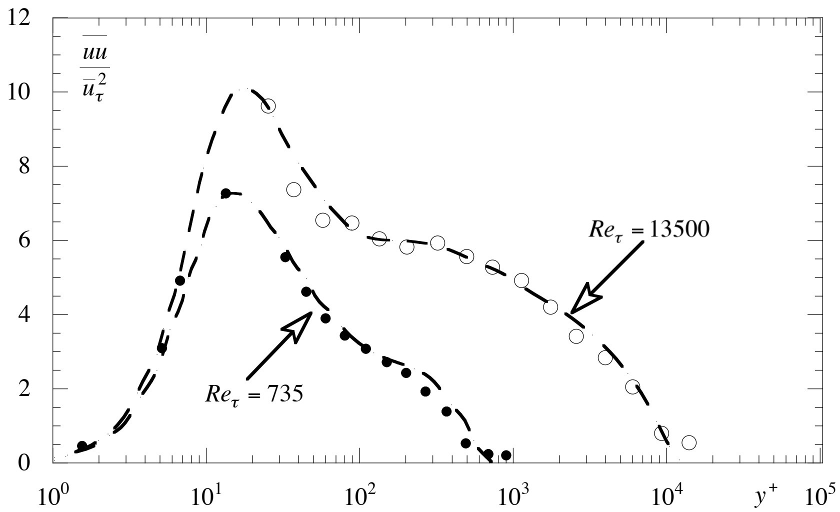
Restrictive to $Re \rightarrow \infty$ and the equilibrium log layer.

==> Streamwise and spanwise velocity intensities depend on Re but NOT wall normal velocity and the Reynolds shear stress

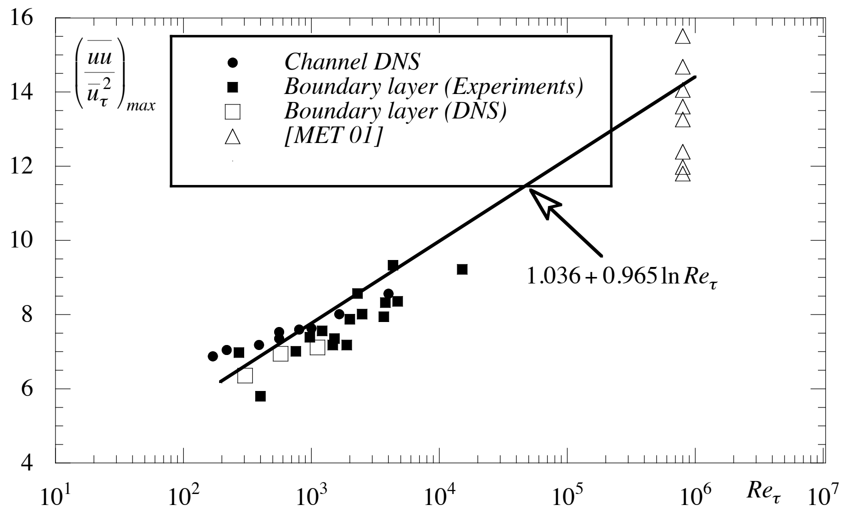
LSM&VLSM
Reynolds shear stresses

- *Turbulent intensity of streamwise velocity fluctuations*

One of the most sensitive and well documented quantity



uu profiles at two different Re (DeGraff & Eaton, 2000) and prediction of Marusic & Kunkel, 2003.

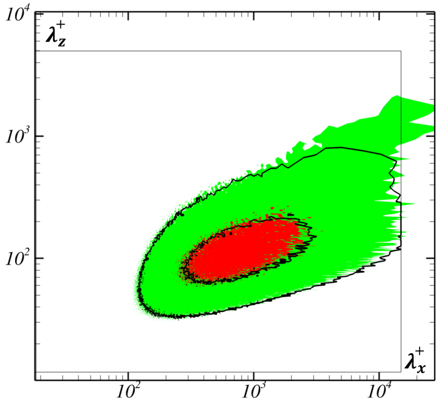


Maximum streamwise turbulent intensity vs Re

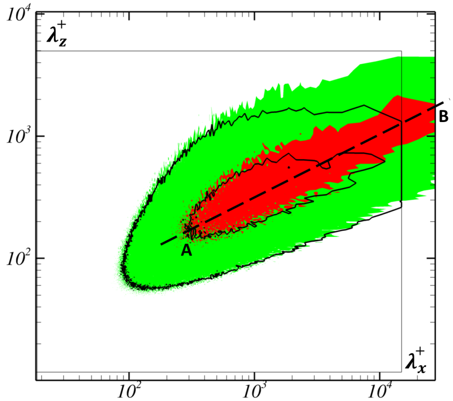
LSM&VLSM
Weighted spectra (LEGI_DNS)

Weighted spectra $k_x^+ k_z^+ E_{u_i' u_i'}$; *Black lines* $Re_\tau = 390$, *colors* $Re_\tau = 1100$

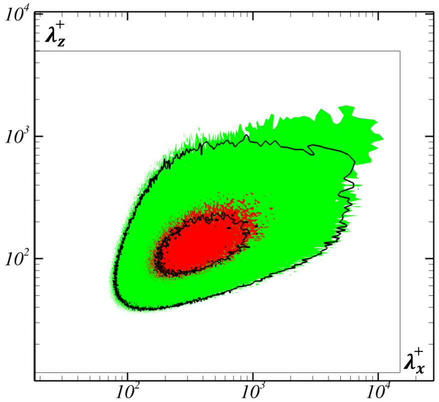
Streamwise; BUFFER LAYER



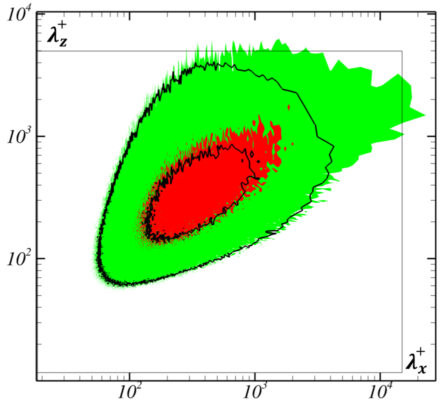
Streamwise; LOG LAYER



Spanwise; BUFFER LAYER



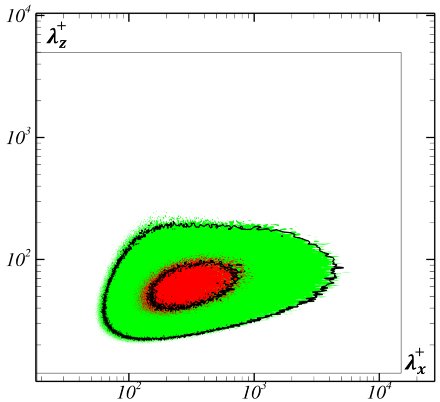
Spanwise; LOG LAYER



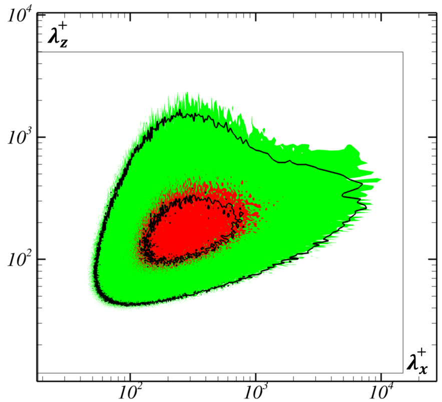
LSM& VLSM
(Roughly) Re independent, robust shear stresses

$$Weighted\ spectra\ k_x^+ k_z^+ E_{u_i' u_i'};\ Black\ lines\ Re_\tau = 390,\ colors\ Re_\tau = 1100$$

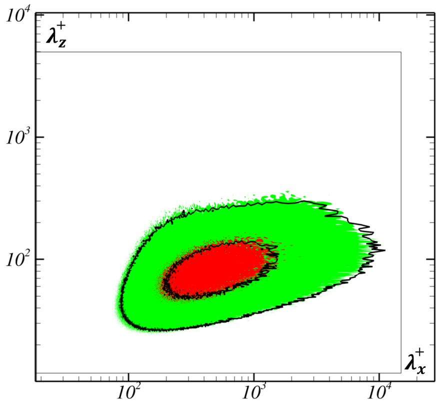
WALL NORMAL; BUFFER LAYER



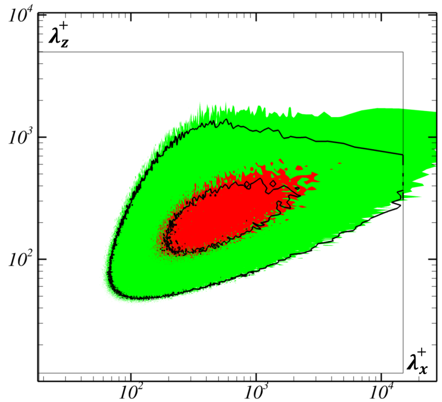
WALL NORMAL; LOG – LAYER



Re – Shear stress; BUFFER LAYER

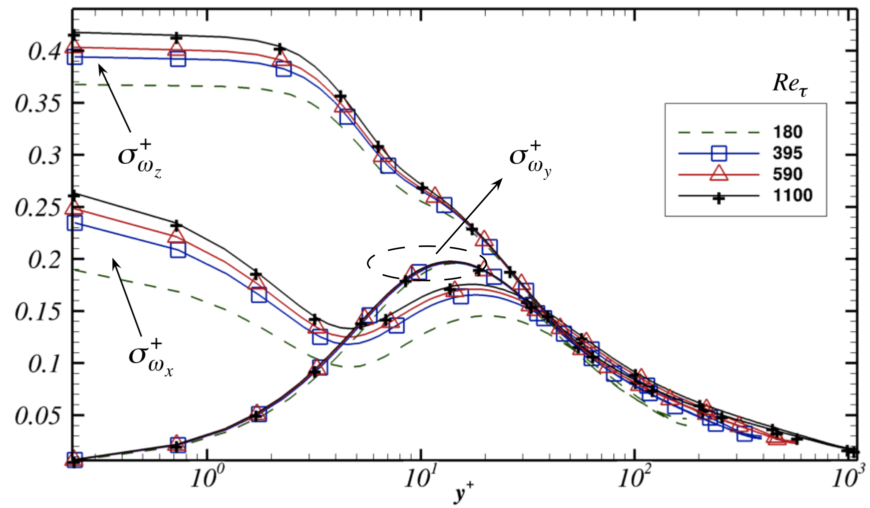


Re – Shear stress; LOG – LAYER



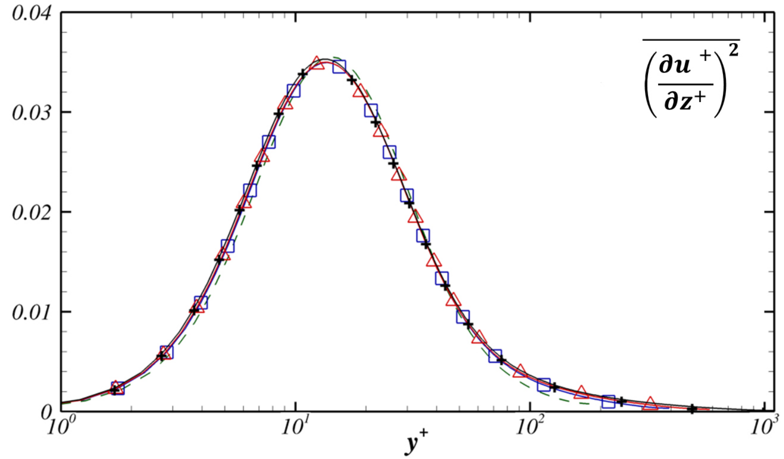
!!!

Some robust LSM independent (roughly speaking) flow quantities: wall normal vorticity and shear layers (Tardu&Bauer, EJM_B 2016)



Vorticity components rms

Wall normal vorticity is spectacularly independent of the Re number

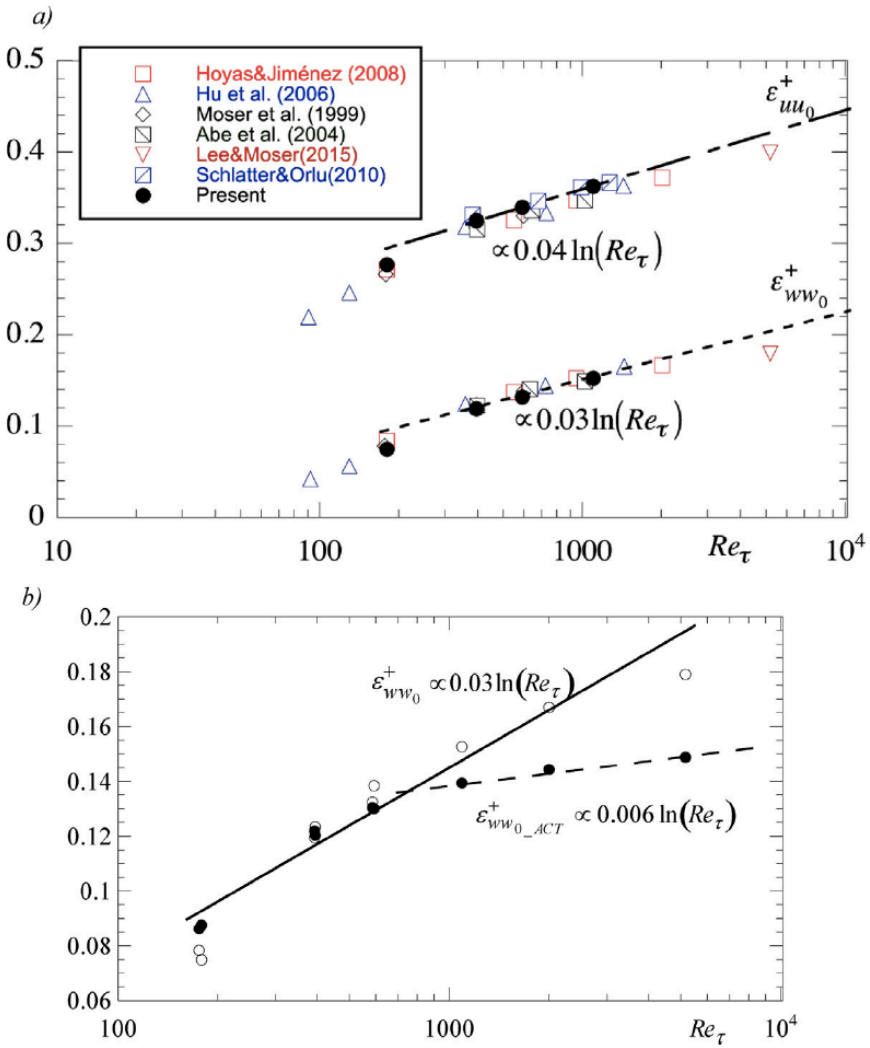


Spanwise gradient of the streamwise velocity shear layers : independent of Re

CONCLUSION : Large number of flow quantities influenced by large - scales

Dissipation (at the wall)

S. Tardu / International Journal of Heat and Fluid Flow 000 (2017) 1–12



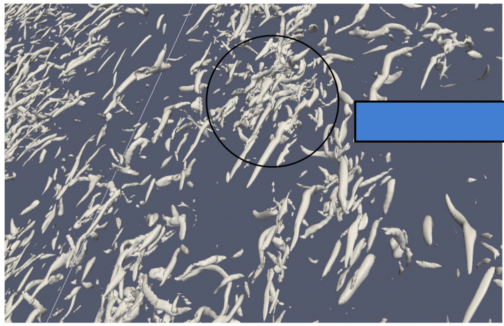
$Re_\tau = 700$: Limit Re number from which LSM effects take over inner active eddies

Fig. 4. *a*) Wall dissipation terms ε_{uu_0} and ε_{ww_0} related to the transport equations of the streamwise and spanwise velocity, versus the Reynolds number

Key elements for modeling_understanding
VORTEX CLUSTERS

- *No body has clearly and irrefutably identified a Large Scale Motion and even less a very large scale motion.*
- *OPT HERE FOR:*
- *LARGE_SCALE MOTION: CLUSTERING OF QUASI_STREAMWISE VORTICES IN THE BUFFER LAYER (EXIST AT ALL REYNOLDS NUMBERS: PACKETS OF QSV.*
- *VERY_LARGE_SCALE MOTIONS: CLUSTERING OF CLUSTERS OF QUASI_STREAMWISE VORTICES: presumably in the log layer and presumably at some large Reynolds numbers.*
- *AIM and PRINCIPAL CONTRIBUTION HERE:*

INTRODUCE A MODEL TO DESCRIBE CLUSTERING and estimate the occurrence probability of CLUSTERS of VORTEX CLUSTERS (VLSM)



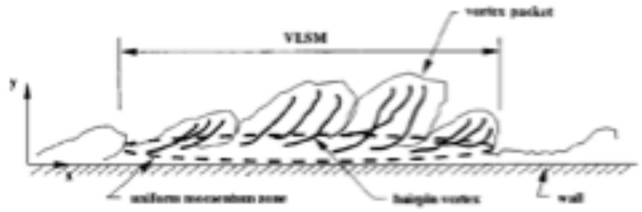
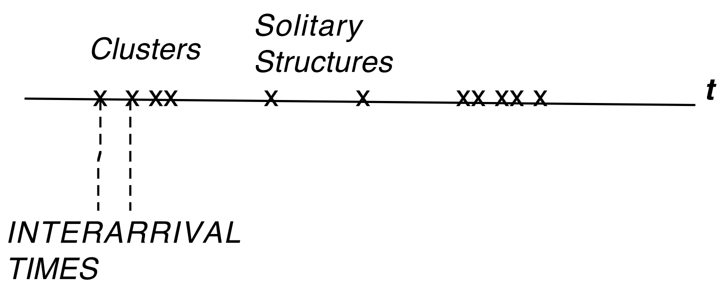
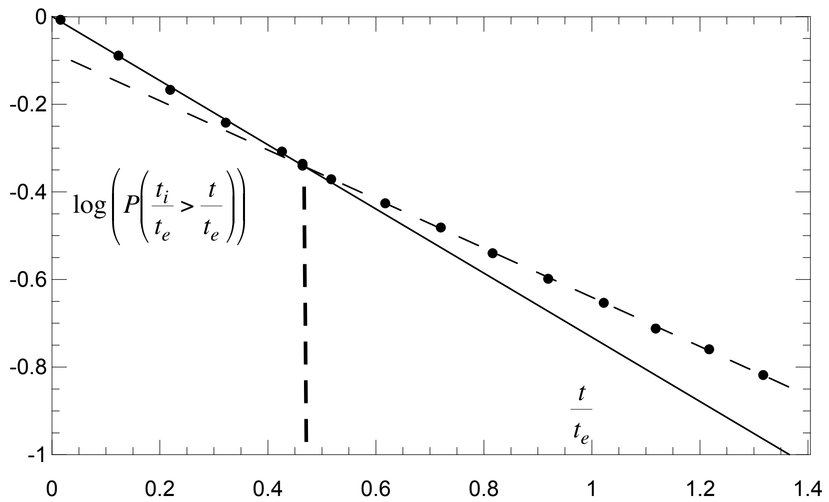


FIG. 7. The conceptual model of the process that creates very large-scale motions. Hairpins align coherently in groups to form long packets, and packets align coherently to form very large-scale motions.

Vortex clusters
Double Poissonian process in time

Stayed longtime enigmatic (to me): no clear model in the literature; there are also some misinterpretation from my point of view (Kailasnath, Sreenivasan, PoF 1993





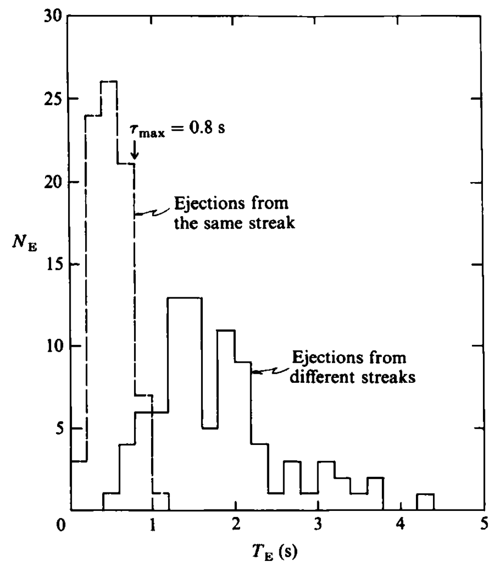


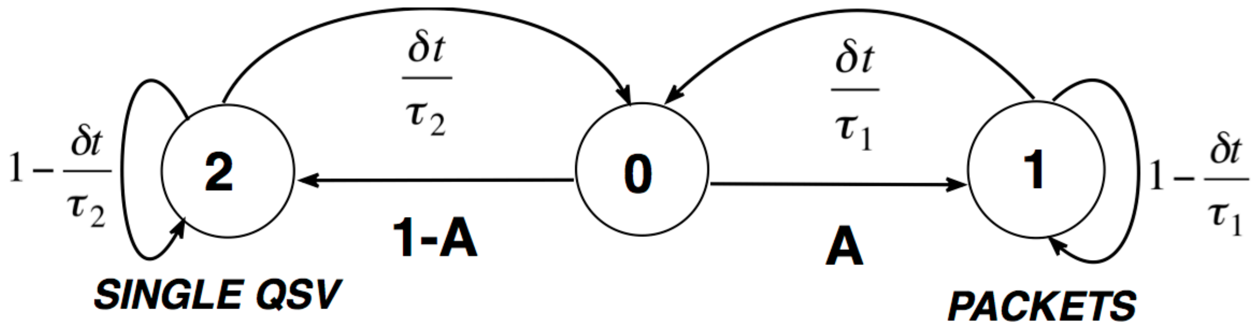
FIGURE 8. Histogram of the distribution of time between ejections T_E for ejections arising from the same and from different streaks. Based on 200 s sample time flow-visualization record.

Bogard&Tiederman, JFM, 1986

Modeling the clusters

Break-point in the interaarival time cumulative probability➔ Markoff Chain to model Double Poisson Process

- Markoff chain that contains 3 states (memoryless process, the outcome depends on the current state. Coupling two independent Poisson processes.
- *This model has been applied to Ice particle intearrival times in clouds (Field et al., 2003)*
- ***State 0*** : Presence (passage) of a Quasi-Streamwise Vortex (QSV) within a given time interval δt
- *States 1 and 2* : Waiting states. Absence of QSV within δt.
- The arrows are annotated with their respective probabilities of occurrence: Ex: the arrow linking state 1 to state 0 represents the observation of an event for a Poisson process with the mean arrival rate $1/\tau_1$
- A is is a measure of clustering
- It is not possible to go from state 1 directly to state 2, without going through the intermediate state 0.



Modeling the clusters

- Transition Matrix:

$$P = \begin{pmatrix} p_{00} & p_{01} & p_{02} \\ p_{01} & p_{11} & p_{12} \\ p_{20} & p_{21} & p_{22} \end{pmatrix} = \begin{pmatrix} 0 & A & 1-A \\ \frac{\delta t}{\tau_1} & 1-\frac{\delta t}{\tau_1} & 0 \\ \frac{\delta t}{\tau_2} & 0 & 1-\frac{\delta t}{\tau_2} \end{pmatrix}$$

*1)Probability of going from state 0 to 1 and remaining in 1 for n time intervals before going to 0

$$p_{011111..10} = p_{01} p_{11}^n p_{10} = A \frac{\delta t}{\tau_1} \left(1 - \frac{\delta t}{\tau_1}\right)^n$$

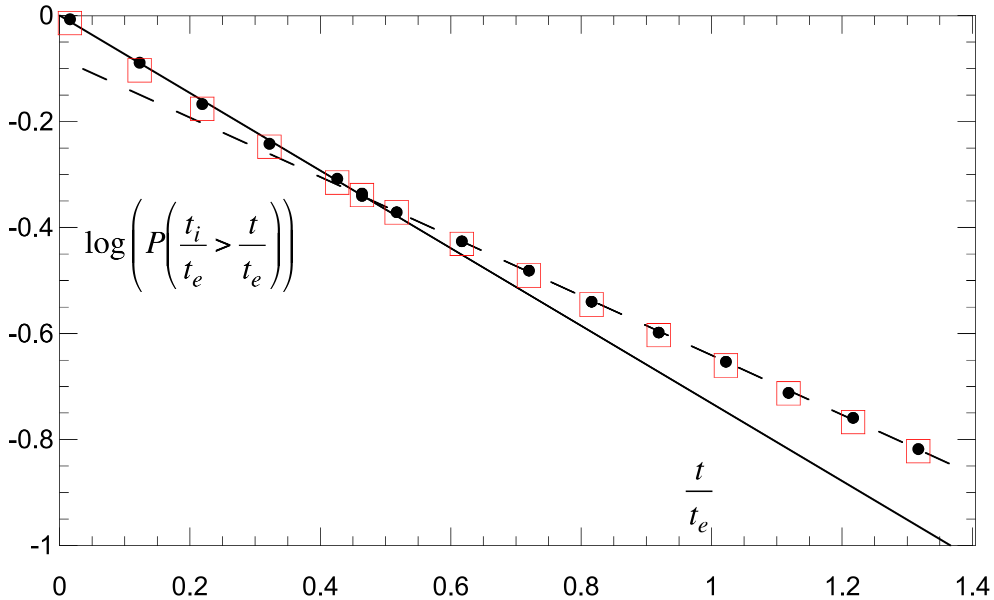
*2)Probability of going from state 0 to 2 and remaining in 2 for n time intervals before going to 0

$$p_{022222..20} = p_{02} p_{22}^n p_{20} = A \frac{\delta t}{\tau_2} \left(1 - \frac{\delta t}{\tau_2}\right)^n$$

Sum 1+2 and taking the limits :Cumulative probability of interarrival times:

$$P(\Delta t > \Delta t_i) = A \exp\left(-\frac{\Delta t}{\tau_1}\right) + (1 - A) \exp\left(-\frac{\Delta t}{\tau_2}\right)$$

Perfect collapse between the model and experiments



$y^+ = 12$, Mean interarrival time between the QSV of the packets $\tau_1^+ = 14$ (MEASURED)

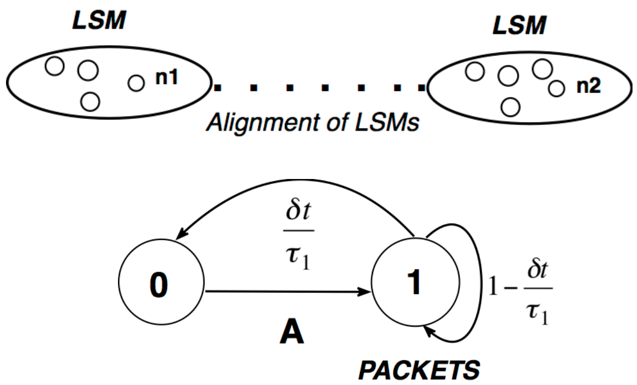
Total process is Poisonnian with $\tau_1 + \tau_2 = \frac{1}{f_r}$; $f_r : QSV$ regeneration frequency (MEASURED)

==> $f_r^+ = 0.014$ ==> $\tau_2^+ = 57$

$$A = \frac{\tau_1}{\tau_1 + \tau_2} = 0.22 \text{ (MEASURED)}$$

Probability of the occurrence of very large scale motions VLSM (clusters of LSM)

- *The interesting point is that the model allows a simple estimation of the probability of having VLSM, i.e. clustering of the packets.*



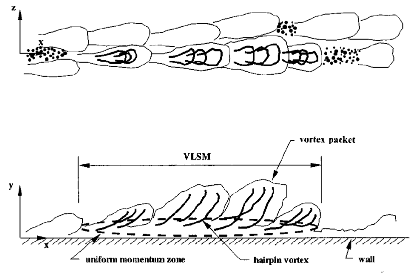


FIG. 7. The conceptual model of the process that creates very large-scale motions. Hairpins align coherently in groups to form long packets, and packets align coherently to form very large-scale motions.

PROCESS :

a- ***Generate the packet number 1 (LSM) with N_1 évents***

➔ ***Go from 0 to 1, wait for the first event for $n_{11}\delta t$ time intervals, then go back to 0 ; go to 1, wait for the second event of the packet for $n_{12}\delta t$ periods , go back to 0 and repeat.***

b- ***Go to 1, wait for $M_{12}\delta t$ time period for the arrival of the second packet and go back to zéro***

c- ***Then repeat (a) for the second packet with N_2 QSV..***

d- ***ETC.***

Probability *p* of the occurrence of very large scale motions VLSM (clusters of LSM)

This probability is proportional to:

$$p \propto A^{N_1 + N_2 + \dots N_\Xi + \Xi - 1}$$

N_i : *Number of structures in LSM i*; Ξ : Number of alligned LSM

$$Uniform\ distribution\ N_i = N;\ Absence\ of\ VLSM : \Xi = 1$$

$$==> \log \frac{p(\Xi > 1)}{p(\Xi = 1)} = (\Xi - 1)(N + 1)\log A \qquad (\Xi \neq 1)$$

Since *log(A)<0*, the slop is negative, and the *VLSM formed from both large LSM (N) and increasingly greater alignment of LSM become less frequent.* ***Larger are LSM rare are VLSM!!!!***

Fine modeling of Large_Scale_Motions (*Undergoing*)

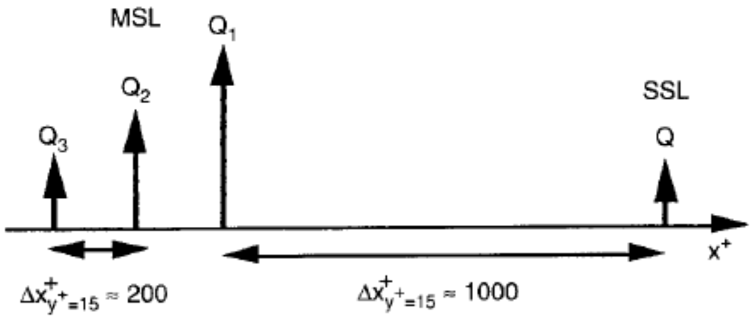
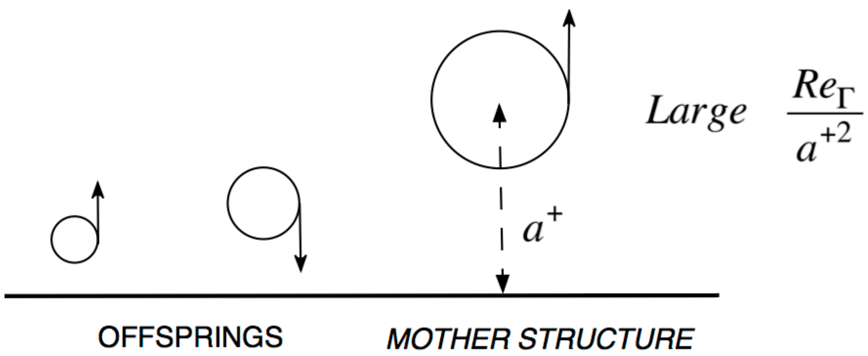


Fig 12. Typical nonlinear driving terms corresponding to multiple and single shear layers



associated with VITA events. Landahl supposes that the nonlinearity is intermittent, the viscosity is important only for a long time after its set-up and that the flow quantities vary slowly in the streamwise direction. In this case, the governing equation for the fluctuating wall normal velocity is

$$\frac{D}{Dt}\nabla^2 v' - \frac{\partial^2 \bar{u}}{\partial y^2}\frac{\partial v'}{\partial x} = q$$

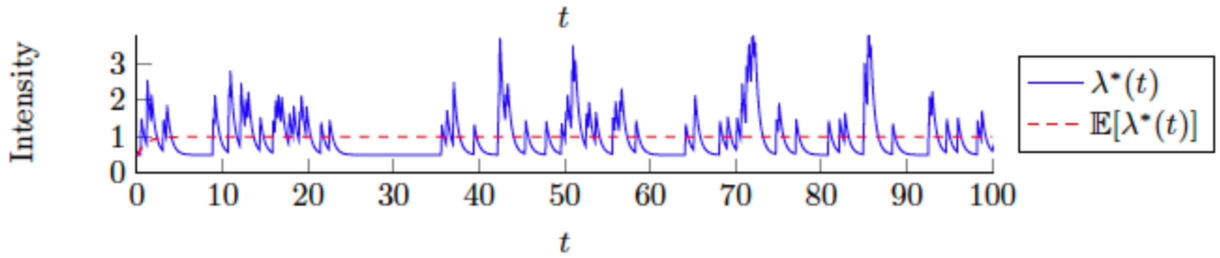
where

$$q \approx \frac{\partial^2}{\partial y^2}\left[\frac{\partial}{\partial x}(u'v') + \frac{\partial}{\partial z}(v'w')\right]$$

stands for the nonlinear terms (Landahl 1990, p. 595).
A statistical model is used by Landahl to describe the source term q in this equation. The conditional nonlinear term is formulated as $q = Kf(x, y, z)\delta(t - t_e)$ where t_e is the "ejection" time and the Dirac function translates the nonlinear intermittency. Here, the constant K is a measure of the strength of the source term. Furthermore, for short and intermediate times

Occurrence of LSM is very similar to the *Hawkes* process

- Self exciting non homogeneous Poisson point process (Hawkes, 1971):
- Seismology: *Earthquake and subsequent aftershocks*, neuroscience, epidemiology, insurance and finance
- Processes whose behavior is modified by the past events which are self excited and externally excited (A QSV of sufficient strength and enough close to the wall –Immigrant in the Hawkes terminology) induce a close in time secondary structure (offspring, children).
- Perfectly compatible with the random non linear excitation of the Landahl's model (previous slight).



Instantaneous arrival rate of a Hawkes process and clusters (packets)

Large_scale-motions and Hawkes process (*undergoing*)

- Excitation function is exponential. Instantaneous rate

$$\lambda^*(t) = \lambda + \sum_{t_i < t} \alpha\, e^{-\beta(t - t_i)}$$

- Covariance density

$$R^c(\tau) = \overline{\lambda^*}\,\delta(t) + R(\tau) = \overline{\lambda^*}\,\delta(t) \quad + \quad \frac{\alpha\beta\lambda(2\beta - \alpha)}{2(\beta - \alpha)^2}\, e^{-(\beta-\alpha)\tau}$$

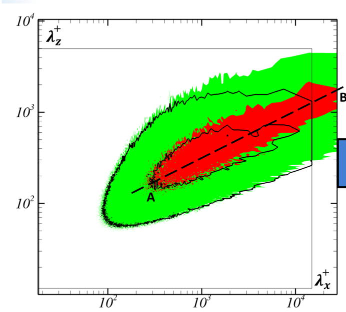
THE PROCESS IS LONG RANGE DEPENDENT

IMPACT OF THE CLUSTERS ON THE LARGE-SCALE SPECTRAL BEHAVIOUR

Large_scale-motions and Hawkes process (*undergoing*)

- ***SPECTRUM:***

$$S(\omega) = \frac{\lambda\beta}{2\pi(\beta-\alpha)}\left(1+\frac{\alpha(2\beta-\alpha)}{(\beta-\alpha)^2+\omega^2}\right)$$



$$LARGE\ SCALE\ CONTRIBUTION\ .\ \mathrm{AT}\ \omega=0\ :\ \frac{\alpha(2\beta-\alpha)}{(\beta-\alpha)^2}$$

$$Both\ \alpha(Re)\ and\ \beta(Re)$$

$$CHALLENGE:$$

$$DEVELOP\ THE\ MODEL\ TO\ PREDICT\ Re\ dependency$$

Happy birthday Fabien

Fabien in Little China at Shenzhen (March 2019). After long researches the whole day, he unfortunately could find anything about ***TOUTANKHAMON.***