Highlights of Fifty Years of Turbulent Boundary Layer Research
Turbulence Colloquium Marseille 2011

James Wallace
Landmarks of Turbulent Boundary Layer Research

Pre – 1961
Development of Hot-wire anemometry & measurement of statistical properties.

1960s
Visualization identifying organized (coherent) structures related to turbulence production.

1970s
Conditional sampling and averaging methods (quadrant analysis, VITA, etc.) developed to quantify properties and effects of organized structures.

1980s
First DNS of turbulent channel and boundary layer flows providing full spatial field properties and access to 3D structural information. First experimental measurements of velocity gradient tensor based properties: vorticity, dissipation rate, etc.

1990s
Development of better methods to identify vortices. Implementation of planar PIV providing new insights to flow structure. Development of field sites for experiments in the ASL at very high Reynolds numbers. Development of high Reynolds number laboratory facilities.

2000s
DNS at significantly higher Reynolds numbers and supersonic Mach numbers. Use of stereo-, tomographic- & holographic-PIV to provide additional insight about flow structure.

2010s
DNS for much higher Reynolds numbers and hypersonic flow ($\text{Re}_\theta \sim 11,000$ & Mach $\sim 12$).
Pre - 1961

1st NBS hot-wire apparatus

Dryden & Kuethe (1929) NACA TR 320


"horseshoe" structure of wall bounded turbulence

Theodorsen (1952) 2nd Midwestern. Conf. on Fl. Mech.
Figure 1. The law of the wall.

\[ \frac{u}{u_r} = \frac{1}{\kappa} \ln \left( \frac{y u_r}{\nu} \right) + \epsilon \]


Figure 2. The law of the wake.

\[ \frac{u}{u_r} = f \left( \frac{y u_r}{\nu} \right) + \frac{\Pi}{\kappa} \Theta \left( \frac{y}{\delta} \right) \]

Coles (1956) JFM 1
Corrsin & Kistler (1954) NACA TN 3133


Klebanoff (1955) NACA Rep. 1247
Figure 7. Space-time isocorrelation surfaces with optimum delay in the boundary layer on a flat plate; $\delta = 33$ mm, $Re = 27900$, $y'/\delta = 0.01$

Grant (1958) JFM 4

Favre, Gaviglio & Dumas (1958) JFM 3

Figure 21. The nine correlations in the boundary layer.

**Figure 6.** Longitudinal space-time correlation of the wall pressure displayed in three dimensions using the data of figure 5.

Willmarth & Wooldridge (1962) JFM 14

**Fig. 11.** Streamlines of the large eddy structure in a plane normal to the mean flow.

Bakewell & Lumley (1967) Phys. Fl. 10
Hydrogen Bubbles

Kline, Reynolds, Schraub & Runstadler (1967) JFM 30

View Multi-media Fluid Mechanics videos 4192, 4497 & 4766 in the Media Library

Corino & Brodkey (1969) JFM 37

BL Interface Bulges

Kovasznay, Kibens & Blackwelder (1970) JFM 41

Blackwelder & Kovasznay (1972) Phys. Fl. 15
Wallace, Eckelmann & Brodkey (1972) JFM 54
Brodkey, Wallace & Eckelmann (1974) JFM 63
Wallace & Brodkey (1977) Phys. Fl. 20

Willmarth & Lu (1972) JFM 55
Lu & Willmarth (1973) JFM 60
Patterns ~
1100 $\Delta x^+$, 1.6$\delta$

Emmerling (1973) MPI für Strömungsforschung Bericht No. 9
Dinkelacker, Hessel, Meier & Schewe (1977) Phys. Fl. 20
VITA Conditional Sampling

Blackwelder & Kaplan (1976) JFM 76

Chen & Blackwelder (1978) JFM 89

Antonia, Rajagopalan, Subramanian & Chambers (1977) JFM 121

Kim & Moin (1986) JFM 162

DNS $Re = 180$
Figure 14. Root-mean-square vorticity fluctuations normalized by the mean shear. (a) In global coordinates: $\omega_u v_{u}^2$; $\omega_v v_{v}^2$; $\omega_w v_{w}^2$; (b) in wall coordinates: $\omega_x$, $\omega_y$ from Kastrinakis & Eckelmann (1983), $\omega_z$ at the wall from Kreplin & Eckelmann (1979).

Figure 12. Measured r.m.s. fluctuating vorticity components normalized with inner scaling $u_*$ and compared to other measured and simulated values. Symbols given in table 2.

Figure 25. Flow structures visualized by fluid markers: (a) particles are generated along a line parallel to the z-axis at $y^* \approx 10$ (oblique top view); (b) particles are initially distributed uniformly on a plane parallel to the wall at $y^* \approx 10$ (top view); (c) particles are generated along a line parallel to the $y$-axis (side view).

Kim, Moin & Moser (1987) JFM 177

Spalart (1988) JFM 187

Figure 19. Vorticity contours, $R_e = 1410$. (a) Streamwise plane; (b) spanwise plane; (c) downstream plane, at 45°; (d) upstream plane, at 45°. Contour levels: $[\omega] (du/u^*)^\beta = 1, 2, 3, \ldots$

Figure 10. Measured turbulent kinetic energy production and dissipation rates normalized with inner scaling $u_*$ and $v$ and compared to other measured and simulated values. Symbols given in Table 2 except for $*$, dissipation neglecting cross-product velocity gradient correlations and $\Phi$, dissipation assuming isotropy.

Balint, Vukoslavčević & Wallace (1991) JFM 228
Spalart (1988) JFM 187

Figure 19. Measured one-dimensional fluctuating vorticity component spectra at $y^+ = 18$ compared to direct numerical simulations of P. R. Spalart (1990, private communication) at $y^+ = 15$.

Figure 21. Measured terms in equation (7) for the transport of total enstrophy normalized with inner scaling $u_+$ and $v_+$. Closed symbols, present measurements; open symbols, Balint et al. (1990): (▼, □), advection (term (7)I); (●, ○), rotation and stretching/compression (term (7)II); (▲, △), viscous diffusion (term (7)III); (■, □), viscous dissipation (term (7)IV).

\[
\begin{align*}
U_j \frac{\partial}{\partial x_j} \left( \frac{1}{2 \Omega_i \Omega_j} \right) &= \Omega_i \Omega_j \frac{\partial U_j}{\partial x_j} + \nu \frac{\partial^2 \left( \frac{1}{2 \Omega_i \Omega_j} \right)}{\partial x_j \partial x_j} - \nu' \frac{\partial \left( \frac{1}{2 \Omega_j \Omega_j} \right)}{\partial x_j}, \\
I & \text{: the rate of advection of total enstrophy;} \\
II & \text{: the rate of rotation and stretching/compression of total enstrophy by the velocity gradient field;} \\
III & \text{: the rate of viscous diffusion of total enstrophy;} \text{ and} \\
IV & \text{: the rate of viscous dissipation of total enstrophy.}
\end{align*}
\]

Antonia, Bisset & Browne (1990) JFM 213
Bernard & Handler (1990) JFM 220

Bernard, Handler & Thomas (1993) JFM 253
FIGURE 20. (a) Streamwise cross-section of a supersonic boundary layer with $Re = 20000$, obtained using Rayleigh scattering; Smith (1989). (b) Streamwise cross-section of a subsonic boundary layer with $Re = 4000$, obtained using oil droplet visualization; Fack (1977). (c) Streamwise cross-section of a computer-generated subsonic boundary layer with $Re = 670$, showing iso-vorticity contours. The flow is a direct Navier–Stokes turbulence simulation; Robinson (1989).
Figure 1b  Conceptual model of the kinematical relationships between (1) ejection/sweep motions and quasi-streamwise vortices in the near-wall region and (2) ejection/sweep motions and arch-shaped vortical structures in the outer region. Model proposed for low-Reynolds-number boundary layers (from Robinson 1990).

Figure 4  Vorticity lines traced from either side of a quasi-streamwise vortex in a boundary layer, showing upright- and inverted-hairpin shapes.
The exact Reynolds stress transport equation can be written

\[ D_t \overline{u_i u_j} = \mu_{ij} + P_{ij} - \frac{u_i u_j}{k} e - \delta_{ij} \overline{u_k u_k} - \frac{2}{3} \rho \delta_{ij} \overline{\partial_k u_k} + \nu \nabla^2 \overline{u_i u_j} \]

where

\[ P_{ij} = -\overline{u_i u_k \partial_j U_j} - \partial_j \overline{u_k u_k} \partial_j U_j \]

is the rate of turbulence production by mean velocity gradients,

\[ \mu_{ij} = -\frac{1}{\rho} \overline{u_i \partial_j p} - \frac{1}{\rho} \overline{u_j \partial_i p} + \frac{2}{3} \rho \delta_{ij} \overline{\partial_k u_k p} - \epsilon_{ij} \overline{u_i u_j} \]

is tensorially consistent near wall 2nd order closure model without ad hoc damping functions

\[ \left( \begin{array}{c}
\frac{\partial u_i}{\partial x_j} \\
\frac{\partial u_j}{\partial x_i}
\end{array} \right) = \left( \begin{array}{c}
\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} \\
\frac{\partial u_2}{\partial x_1} + \frac{\partial u_1}{\partial x_2} + \frac{\partial u_3}{\partial x_2} \\
\frac{\partial u_3}{\partial x_1} + \frac{\partial u_1}{\partial x_3} + \frac{\partial u_2}{\partial x_3}
\end{array} \right) = \left( \begin{array}{c}
0 \\
0 \\
0
\end{array} \right) \]
Choi, Moin & Kim (1993) JFM

Figure 1. (a) Three-dimensional view of detection planes (b) schematic diagrams of out-of-phase v-control.

Figure 10. Production ($P_k$) and dissipation ($\epsilon_k$) of the turbulence kinetic energy: ---, no control; ---, v-control; ---, w-control. (a) In global coordinates; (b) in wall coordinates. In coordinates, values are non-dimensionalized by the actual wall-shear velocity.

Figure 14. Root-mean square vorticity fluctuations normalized by the wall-shear velocity in global coordinates: ---, no control; ---, v-control; ---, w-control. Note that $y/\delta = -1$ corresponds to the lower location.
Saddoughi & Veeravalli (1994) JFM 268

Figure 3. Trajectory analysis technique (TRAT) based on quadrant-sequences on the \((u,v)\)-plane. \(-\cdots-\), \(H = 1.07\); \(--\cdots--\), \(h = 0.25\).

Figure 13. Predictions of near-wall temperature fluctuations associated with the key flow patterns using the autoregressive (AR) model: ---, measurements; \(---\cdots\), AR model prediction. (a) Q2-Q1-Q4; (b) Q2-Q3-Q4; (c) Q4-Q1-Q2; (d) Q4-Q3-Q2; (e) Q3-Q2-Q3.

Nagano & Tagawa (1995) JFM 305


Folz & Wallace (2010) Physica D 239
Jeong, Hussain, Schoppa & Kim (1997) JFM 332

Figure 2. Top view of the isosurfaces of $\lambda_2 = -0.03$ in the range $0 < y^+ < 60$.

Figure 13. Coherent Reynolds stresses at $x = 0$ in E1: (a) $- (u - U) (v)$ for SP, contour levels = (0.3, -0.534, 1.94); (b) $- (v) (w)$ for SP, contour levels = (0.2, -0.868, 1.22); (c) $- (u - U) (w)$ for SP, contour levels = (0.7, -1.34, 4.23); (d) $- (u - U) (w)$ for SN. Relative locations of Q1, Q2, Q3 and Q4 events with respect to the CS center are shown in (a).

Figure 14. (a) Vortex lines traced outside CS

Schoppa & Hussain (2002) JFM 453

Figure 10. Conceptual model of an array of CS and their spatial relationship with experimentally observed events discussed in the text: (a) top view; (b) side view; (c) structures at cross-section F/G in (a); (d) expanded views of structures C and D in (a,b), showing the relative locations of Q1, Q2, Q3, Q4, E and H. A schematic demonstrating the counteracting precession of SN in the $(x, z)$-plane due to background shear is shown in (e). The arrows in (b) denote the sections of figure 9(a-e).
Honkan & Andreopolous (1997) JFM 350

Ong & Wallace (1998) JFM 367

\[ \bar{\Omega}_x \bar{\Omega}_y = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Omega_x \Omega_y P(\Omega_x, \Omega_y) d\Omega_x d\Omega_y \]
Barenblatt, Chorin & Prostokishin (2000) JFM 410

\[
\eta = \frac{u_y}{v}
\]

\[
\phi = \frac{u}{u_*} = \left( \frac{1}{\sqrt{3}} \ln Re + \frac{5}{2} \right) \eta^{3/2 \ln Re}
\]

\[
\psi = \frac{1}{\alpha} \ln \left( \frac{2 \alpha \phi}{\sqrt{3} + 5 \alpha} \right) = \ln \eta, \quad \alpha = \frac{3}{2 \ln Re}
\]

Figure 16. (a) The experiments of: *, Erm & Joubert (1991); [], Smith (1994); <, Krogstad & Antonia (1998); and >, Petrie et al. (1990). (b) ▽, The data of Winter & Gaudet (1973). (c) **, The data of Bruns et al. (1973) and Fernholz et al. (1995). (d) The data of all experiments except those by Naguib (1992) and Nagib & Hites (1995), Bruns et al. (1992) and Fernholz et al. (1995): O, Collins et al. (1978); ▽, Petrie et al. (1990); ±, Erm (1988); O, Putell et al. (1981); *, Djenidi & Antonia (1993); ×, Warnack (1994); <, Krogstad & Antonia (1998); ▽, Winter & Gaudet (1973). All the data in (a–d) collapse on the bisectrix of the first quadrant in accordance with the universal form (14) of the scaling law (5). (e) (i) The data of Naguib (1992) and Nagib & Hites (1995) show a systematic deviation from the bisectrix of the first quadrant. (ii) The data of Krogstad & Antonia (1998) related to rough walls: the experimental points lie much lower than bisectrix. For the evaluation of \( \psi \) the value \( \alpha = 3/2 \ln Re \) was taken. (f) The data of Hancock & Bradshaw (1989) show the parallel shift from the bisectrix of the same order as in the experiments by Nagib & Hites: *, Nagib & Hites; *, Hancock & Bradshaw, \( u'/U = 0.0003, 0.024, 0.026 \); ×, Hancock & Bradshaw, \( u'/U = 0.040, 0.041 \); O, Hancock & Bradshaw, \( u'/U = 0.058 \).
Re₀ = 1577
Mach = 2.5

Guarini, Moser, Shariff & Wray (2000) JFM 414


Figure 1. Schematic of PIV photographic recording system. The streamwise–wall-normal plane of a zero-pressure-gradient boundary layer is illuminated by a vertical laser light sheet and imaged by a side-viewing 4 in. x 5 in photographic camera.

Adrian, Meinhart & Tompkins (2000) JFM 422

Figure 7. Root-mean-square streamwise velocity scaled and plotted with mean variables. • $Re = 590$; ▲, $Re = 340$; ○, Rouse et al. (1994); ●, Kawai & Abe (1989); $Re = 2350$; ---, Morkovin (1958); $Re = 1410$.

Figure 11. Near-wall realization at $Re = 930$ showing four hairpin vortex signatures aligned in the streamwise direction. Instantaneous velocity vectors are viewed in a frame-of-reference moving at $U_1 = 0.8U_e$, and scaled with mean variables. Vortex heads and inclined shear layers are indicated schematically, along with the elements triggering a VITA event.

Adrian, Meinhart & Tompkins (2000) JFM 422

Figure 14. Realization of the $Re = 930$ boundary layer showing hairpin vortex heads along the boundaries separating regions of uniform-momentum fluid. The black lines separate the flow field into zones, labelled I, II, III, in which the streamwise momentum is nearly uniform: (a) instantaneous velocity vector map viewed in a convecting frame of reference $U_1 = 0.8U_e$, and scaled with mean variables, (b) contours of constant $m$-momentum.


Figure 10. (a) Schematic of a hairpin vortex normal to the wall and the induced motion. (b) Projection of the hairpin vortex on the streamwise–wall-normal plane. The red square indicates the position of the plane, and it intersects $Re$ concentrated on the bottom.

Hairpin “packet”
\[ A_{ij} = \frac{\partial U_i}{\partial x_j} \]
\[ \dot{\lambda}^3 + P \dot{\lambda}^2 + Q \dot{\lambda} + R = 0, \]
\[ P = -A_{ii}, \]
\[ Q = \frac{1}{2} P^2 - \frac{1}{3} A_{ik} A_{ik}, \]
\[ R = -\frac{1}{3} P^3 + \frac{1}{2} A_{ik} A_{kn} A_{nk}. \]
\[ D = \frac{\dot{\lambda}^2}{4} R^2 + Q^3. \]

**Figure 5.** Top view of the computational domain showing regions of positive discriminant and their spatial association with Reynolds stress events \((u'v')\).

**Chacin & Cantwell (2000) JFM 404**

**Figure 1.** Summary of three-dimensional, incompressible flow patterns (from Soria et al. 1994).

**Figure 19.** Joint probability density function of the \(Q\) and \(R\) invariants of velocity gradient tensor at \(z^+ = 125\).

**Andreopolous & Honkan (2001) JFM 439**

**Figure 3.** Time-averaged Reynolds-stress \((u'v')\) generating events associated with the four incompressible flow patterns. Data taken from the entire boundary layer.
Carlier & Stanislas (2005) JFM 535

**Table 6. Number of eddy structures detected.**

<table>
<thead>
<tr>
<th>$R_0$</th>
<th>$V_\infty$</th>
<th>$V_\star$</th>
<th>$V_\star$</th>
<th>$V_\star$</th>
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<th>$V_\star$</th>
<th>$V_\star$</th>
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<td>10579</td>
<td>10571</td>
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<td>--</td>
<td>2096</td>
<td>2123</td>
<td>--</td>
<td>--</td>
<td>888</td>
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<td>2408</td>
<td>--</td>
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<td>7303</td>
<td>2342</td>
<td>--</td>
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<td>756</td>
</tr>
</tbody>
</table>

**Figure 22. Examples of accepted eddy structures in the $(e_\infty, e_r)$-plane at $R_0 = 7500$.**

**Figure 25. Averaged eddy structures in the $(e_\infty, e_r)$ normal to the wall plane at $R_0 = 7500$, 7500, 10500 and 125 (clockwise from the top left-hand side). The grey scale out-of-plane component.**

**Figure 10: Orientations of the various planes used in the two series of PIV measurements:**
1. $(e_\infty, e_r)$; 2. $(e_\infty, e_\perp)$; 3. $(e_\perp, e_r)$; 4. $(e_\perp, e_\perp)$; 5. $(e_\infty, e_\perp)$

**Figure 30. Mean vorticity profiles of eddy structures: $\nabla \times (e_\infty, e_r)$-plane and $R_0 = 7500$; $e_\infty = 7500$; $(e_\infty, e_\perp)$-plane and $R_0 = 10500$; $(e_\perp, e_\perp)$-plane and $R_0 = 13500$; $(e_\perp, e_r)$-plane and $R_0 = 19000$; r.m.s. spanwise vorticity; Van Driest profile.**

**Figure 34. Probability map of the location of ejection compared to positive eddy structure and positive eddy structure compared to ejection at $y^+ = 50$ and $R_0 = 7500$ in the $(e_\infty, e_r)$-plane.**
(a) Fixed point positive eddy structure; moving point, ejection. (b) Fixed point, ejection; moving point, positive eddy structure.
Hutchins & Marusic (2007) JFM 579


VLSMs

Del Alamo, Jimenez, Zandonade & Moser (2004) JFM 500
Re$_\theta$ $\sim$ 2600  
Mach $\sim$ 3

Re$_\theta$ $=$ 950 - 1350  
Mach = 2

Pirozzoli, Bernadini & Grasso (2008) JFM 613
(2010) JFM 648a
Mathis, Hutchins & Marusic (2009) JFM 628

**Figure 5.** Example of large-scale decomposition on the fluctuating $u$ velocity signal: (a) inner-peak location $z^+=15$; (b) outer-peak location $z/\delta=0.08$; (i) raw signals, with $71\%$ of correlation; (ii) large-scale components, with $72\%$ of correlation. Dashed vertical lines show region of negative large-scale $u'_L$ fluctuation.

**Figure 13.** Comparison of correlation coefficient between the large-scale component and the filtered envelope of the small-scale component: (a) $R$ plotted in inner-scale $z^+$ unit; (b) $R$ plotted in outer-scale $z/\delta$ unit.

**Figure 8.** Wall-normal evolution of the degree of amplitude modulation: (a) pre-multiplied energy spectra of the streamwise velocity fluctuation $i_s\phi_u/U^+$; (i) correlation coefficient $R(i_s')$ between the large-scale component and the filtered envelope of the small-scale component; (c) mean velocity profile; $Re_\tau=7300$. 
Wu & Moin (2009) JFM 630

Figure 17. Zoomed view of the highlighted near-wall small structure in figure 16 overlaid with local instantaneous vortex lines. Iso-surfaces are coloured using $\gamma^*$. 

Wu (2010) JFM 664

Figure 16. Growth parameters of the present boundary layer with free-stream passing wakes. 

- Dotted: $10^{-3} Re/\lambda$; dashed: $10^{-2} \tau / \lambda$; solid: $R^*$; dash-dotted: $10^{-2} Re$; 
- diamond: solutions; diamond, Pettit, Klebanoff & Buckley (1981); circle, Adrian et al. (90); square, DeGraaf & Eaton (2000).

Figure 15. Zoomed view of the highlighted Kelvin-Helmholtz structure in figure 14 overlaid with local instantaneous vortex lines. (a) $\theta = 0$ and (b) $\theta = 0.05$. 

Expansion of structures resolved using $Q$ and temperature over $1550 < Re < 1850$. Iso-surfaces are coloured as of $\gamma^*$. (a) $\theta = 0$ and (b) $\theta = 0.05$. 

Wu & Moin (2009) JFM 630

Wu (2010) JFM 664
Digital Holography

Sheng, Malkiel & Katz (2009) JFM 633

\[ \text{Re}_T = 1470 \]

Elsinga, Adrian, Oudheusden & Scarano (2010) JFM 644

\[ \text{Re}_\theta = 34,000 \]

Mach = 2

Tomographic PIV

Figure 1. Test facility and DHM set-up

Figure 2. (a) Instantaneous vortex distribution detected by the \( Q \) criterion (green) and low-speed zones (blue, \( u < 0.8U_c \)) for \( 0.15 < y/\delta < 0.47 \). (b) A contour plot of the \( u \) component of velocity at \( y/\delta = 0.2 \).

Figure 7. Conditionally averaged three-dimensional flow structure and wall stress based on a local stress minima, \( \tau_z < K\Delta(\tau_z) \), for \( x = z = 0 \). (a) Release of \( \tau_z \) and vortex lines. (b) Conditionally averaged near-wall vortex lines and distribution of \( \tau_{z'}(\Delta x, 0, \Delta z)/(\tau_z) \). Insert: \( x-\gamma \) projection of the vortex lines.

Figure 6. Conditional eddy (a, b) given a negative spanwise swirling event at \( y/\delta = 0.35 \) visualized using the \( Q \) vortex detection criterion (green) and low velocity region (blue, \( \bar{u} < \bar{u}_c \)) with corresponding velocity vector plot in the \( x, y \) plane at \( r_z = 0 \) and \( x, z \) cross-sections at \( y/\delta = 0.2 \) (c, d). The velocity vectors are relative to the eddy convective velocity \( \bar{u}' \) at \( y/\delta = 0.35 \) indicated in the upper left corner of each plot. The dashed lines indicate \( \bar{u}_c = 0 \).

$Re_\theta \sim 2500$


$Re_\theta = 1400 & 4300$

Schlatter, Li, Brethouwer, Johansson & Henningson (2009)
Int. Jour. Heat & Fluid Flow 31

Schlatter & Örlü (2010) JFM 659
Dennis & Nickels (2011) JFM 673
Stereo PIV
Reₜ ~ 4700

Jimenez, Hoyas, Simens and Mizuno (2010) JFM 657

Figure 3. (a) Typical sections of $\omega$ in the boundary layer, showing instantaneous potential flow deep into the reverse region. $Re_\theta$ ~ 300–900. (b) Probability density functions of the vorticity magnitude in section 30.53, showing the development away from the wall of the transitional data at $u'$/σ = 0.4; --, 0.55; ---, 0.65; -----, 1.2. The dashed vertical line is the limit used to define transitional flow, slightly larger than a single histogram bin. (c) Interception factor, $\zeta$. BLS in the present simulation; ..., BL3; ..., BL3.2; ..., from experimental velocity measurements at $Re_\theta$ ~ 8000 (Konoshima, Khmelev & Blackwelder 1970); ..., from temperature measurements at $Re_\theta$ = 1100–4000 (Murta, Tao & Buddhaw 1982).

Figure 11. Iso-surfaces of the instantaneous velocity gradient tensor of the present simulation on Top view (a) Perspective view. The magenta surface is from left to right and the wall-normal direction of the box are approximately 18 × 9 times the boundary-layer thickness at the centre of the box, spanning $Re_\theta$ = 1600–3000. The thickness is defined by the distance to the wall, from $y^+$ = 0.3–0.4 for the deepest blue to $y^+$ = 0.5 for the brightest red.

Figure 9. Instantaneous sections of the fluctuations in the boundary layer: $u$ (a, b), $v$ (c, d), $w$ (e, f), $p$ (g, h) (a, c, e, g) The $x$–$y$ sections, in $Re_\theta$ = 1670–2000, and (b, d, f, h) the $z$–$y$ sections at $Re_\theta$ = 1670. All the fluctuations are normalized with the $x$-dependent friction velocity, and the coordinates are normalized with $\delta_99$ at $Re_\theta$ = 1670. In all the sections the dark areas are below −0.5 wall units, and the lighter ones above +0.5.

Figure 16. (Colour online) Conditionally averaged swirling

Figure 6. (Colour online) Visualisation of vortices with high- and low-speed structures. Black iso-surface: $|\lambda_1| = 0.12|\lambda_\text{max}$. Blue iso-surface: $\lambda_\text{min} = 0.7$. Red iso-surface: $\lambda_\text{min} = 0.7$.
Guala, Metzger & McKeon (2011) JFM 666

Re_θ = 1515 – 11,356
Mach = 0.3 – 11.9

Duan, Beekman & Martin (2011) JFM 672
Fig. 2: Examples of (a) an individual turbulent spot at \( Re_y = 200 \), (b) merged turbulent spots at \( Re_y = 500 \) and (c) developed turbulence at \( Re_y = 1840 \) in the boundary layer near the wall marked by contours of enstrophy. The yellow dashed lines demark the parts of the flow in which data was used to calculate the statistics.
Summary

- There has been remarkable progress in turbulent boundary layer research in the past 50 years, particularly in understanding the structural organization of the flow. Consensus exists that vortices drive momentum transport but not about the exact form of the vortices or how they are created and sustained.

- This progress has been fueled by developments in experimental instrumentation (multi-sensor hot-wire anemometry and PIV) but most of all with the advent of DNS in the 1980s and its subsequent advances.

- Further progress has been made by the development of high Reynolds number laboratory facilities and the use of field sites to study the very high Reynolds number atmospheric surface layer under near neutral stability conditions.

- Challenges for the future:
  - Incorporating the knowledge of the structure of turbulent boundary layers into models, including RANS and subgrid scale LES models.
  - Further extending the knowledge gained for zero pressure gradient, smooth wall boundary layers to the complexities of accelerating and decelerating boundary layers and flows with rough walls.
  - Continuing to develop and implement methods to control turbulent boundary layers that occur in real engineering applications.
Highlights of Fifty Years of Turbulent Boundary Layer Research

Pre – 1961

SLIDE 1
Title

SLIDE 2
Summary of periods and highlights by decades

SLIDE 3
Early hot-wire measurements. Some done in Delft by Burgers and co-workers even earlier in the 20s.

SLIDE 4
Similarity laws for “overlap” and “wake” regions.

Millikan: “Law of the wall”

Coles: “Law of the wake”

SLIDE 5
Townsend: RMS distributions of velocity fluctuations and estimate of the TKE balance from hot-wire measurements.

Corrsin & Kistler: “Superlayer” properties and intermittency function in TBL

Klebanoff: TKE production and dissipation rate estimates. All the determinations of the dissipation rate from this period were crudely estimated as the residue of the other terms.

SLIDE 6
Favre et al: Space-time isocorrelation contours with optimum time delay. Probes were separated in both the streamwise and wall normal directions. Fixed probe at about y+ = 40. Note high aspect ratio of correlation in x-y plane compared to y-z plane. Note also that a small correlation remains all the way out to y = 0.3δ.

Grant: Spatial correlation tensor components at several locations of the fixed probe in the boundary layer. He inferred structure from these correlations.

SLIDE 7
Willmarth & Wooldridge: Wall pressure space-time correlation function with two probes of varying separation in the streamwise direction. One horizontal axis is time and the other is downstream distance. The vertical axis is the correlation level. The ridge flowing out to the lower right of the figure shows the cumulative effect of
eddies of different scale on the wall pressure with increasing time and distance. The decay in correlation is interpreted as the increasing loss of the effect of smaller eddies.

Bakewell & Lumley: Streamlines in the cross-stream plane of a pipe flow of glycerin as revealed by proper orthogonal decomposition of hot-film data and their suggested eddy structure.

SLIDE 8
Visual experiments that excited the research community about organized coherent motions in wall bounded flows.

Kline et al.: Low-speed streaks revealed by hydrogen bubbles and their “bursting”.

Corino & Brodkey: “Ejection” and “sweep” coherent events revealed by particle motion near the wall in a pipe flow viewed in a moving frame of reference.


SLIDE 9
Kovasznay et al.: Intermittency function, point averages of “fronts” and “backs” of potential flow bulges and a sketch of them.

SLIDE 10
Wallace et al.: Quadrant analysis of the Reynolds shear stress in a channel flow. Plot of covariance integrand, uv dudv, by quadrant and as function of distance from wall.

Willmarth and Lu: Quadrant analysis for boundary layer with “hole” of constant Re Stress to accentuate large amplitude events.

SLIDE 11
Several hundred small holes covered with a mirrored silicone rubber foil. Using interferometry and a high speed movie camera, the instantaneous fringes on each element were used to determine local wall pressure after calibration.

Figure shows pressure pulses being convected downstream over one row of transducers. Patterns persist for more than 1100 viscous length scales (1½ the boundary layer thickness). Convection velocities are about ¾ of the freestream velocity.

SLIDE 12
Blackwelder and Kaplan: Intention was to detect turbulent “bursts” using Variable Integral Time Averages (VITA) of conditionally sampled data. Condition was that the local square of the streamwise velocity fluctuation minus the square of the local mean be larger than some chosen threshold. This detected events with large du/dt.
The double peaks in the conditional averaged Re stress are roughly related to the Q2 and Q4 quadrants. Simultaneous rake measurements show that these events have great coherence in the wall normal direction.

Chen & Blackwelder: Passively heated wall and a rake of X-array hot-wires. Highly coherent ramps in the temperature fluctuations were observed. Conditioning on these ramps, conditional velocity fluctuation averages were obtained that show the outward motion of warmer, lower momentum fluid downstream of the front followed by inward motion of cooler, higher momentum flow upstream.

Antonia et al.: Similar study using heat as a passive scalar marker. Fig. shows conditional averages of u, v and theta and the momentum and heat fluxes in the inner layer of the TBL.

SLIDE 13
Head & Bandyopadhyay: Smoke visualization of boundary layer structure viewed in inclined planes and interpreted as hairpin vortices.

Balint et al.: A similar study with wall layer and potential flow separately marked by smoke and the tripping of the boundary layer varied. Photo shows the evolution and growth of wall layer structures which eventually penetrate the potential flow. The potential flow is also ingested deeply into the turbulent boundary layer.

Townsend: Proposed the attached eddy model

Perry et al.: Used this conceptual model of attached hairpin eddies, rolling up and lifting up out of near wall sheets of vorticity, to construct a theoretical model that attempts to explain many of the statistical features of the boundary layer, including the log layer.


SLIDE 14
Kim & Moin: Vorticity (vortex lines) showing hairpin and Ω-like shapes in a turbulent channel flow DNS. Cross-stream plane cut through the leg of the vorticity line bundle in the upper right figure shows that this is truly a vortex as revealed by the velocity vector projections on this plane.

SLIDE 15
Kim Moin & Moser: Their DNS was accepted by experimental researchers in part because of the flow visualization they did of simulated hydrogen bubbles that revealed the same structure as in physical experiments.

In this paper, they showed the first DNS distribution of the rms vorticity components and other statistics of the vorticity field.
Balint et al.: We published our rms vorticity component distributions and other vorticity field statistics, experimentally measured with our minature 9-sensor probe, that year in the Proceedings of the 1st European Turbulence Conference.

SLIDE 16
Spalart: A year later, in 1988, he published the first DNS of a turbulent boundary layer where he employed the so-called “fringe” method to rescale the flow allowing him to employ periodic boundary conditions in the streamwise direction. The figures are of the TKE budget and contours of vorticity projected onto streamwise and cross-stream inclined planes of the flow.

Balint et al.: Experimental values of the turbulent production and dissipation rates are compared to Spalart’s DNS values and the Kim, Moin and Moser DNS channel flow values in the figure on the right.

SLIDE 1
Balint et al.: Vorticity fluctuation component spectra compared to Spalart’s DNS.

Distribution of the terms of the transport of total enstrophy equation.

SLIDE 18
Aubry et al.: Expansion of the wall region using POD to obtain low-dimensional sets of ODEs. Streamwise rolls are revealed that have intermittent Reynolds stress “burst” characteristics. This was one of the first applications of low-dimensional chaotic dynamical systems theory to realistic turbulent open flows.

Antonia et al.: A rake made up of an array of 8 X-array hot-wires was used to construct sectional streamlines and contours of the large-scale vorticity in streamwise planes at several Reynolds numbers. Large-scale vortices (foci) and saddle points of high strainrate are evident in this frame of reference traveling to the left at 0.8 of the freestream velocity. Variation with Reynolds number is seen in the figure in the lower right.

SLIDE 19
Bernard et al.: Lagrangian analysis of the Reynolds shear stress that decomposes it exactly into (1) the correlation of $u$ at the terminal point, $a$, with $v$ at the set of initial points, $b$, (2) a “displacement transport” term and (3) an “acceleration transport” term. For large enough mixing times, this $u_a v_b$ bar correlation goes to zero, as seen in the distribution on the right. The displacement transport term is simply a sort of mixing length/mean gradient type effect. The acceleration transport term produces a significant fraction of the Reynolds stress, having a positive or negative contribution depending on position relative to the wall.

The upper right figure shows the pdfs of the particle displacements sorted by the quadrants of quadrant analysis as a function of $y^+$. 
Their group also identified quasi-streamwise vortices with a recognition algorithm and studied particle displacements and Reynolds stress creation in relation to these vortices as seen in the middle lower figure.

SLIDE 20
Spina et al: Studied the structure of supersonic turbulent boundary layers adopting methods used in subsonic, low Reynolds number flows such as the VITA technique and quadrant analysis.

SLIDE 21
Robinson: Analyzed the Spalart DNS to study the structure of the flow. Low pressure was used as a criterion to detect vortices. Few complete hairpins were observed, but this could have been a result of the threshold values set. The relation of low-speed streaks and Q2 and Q4 Reynolds stress to the vortices is clearly seen. Robinson believed that hairpin-shaped vorticity lines are simply a result of their distortion by quasi-streamwise vortices, and that they do not necessarily, themselves, indicate the presence of true hairpins.

SLIDE 22
Tsinober et al.: Use of a 12-sensor hot-wire probe to demonstrate, experimentally, the most probable alignment of the vorticity vector with the intermediate eigenvector of the rate of strain tensor. This had previously been seen in DNS of both isotropic and shear flow turbulence and is now known to be a general characteristic of all turbulent flows.

Durbin: Tensorially consistent 2nd order closure modelling of the Reynolds stress transport equation. Applied to channel and boundary layer turbulent flows with and without pressure gradients and to flows around 90 deg. bends. Figures show model values of turbulence intensities and friction coefficient distributions compared to experimental values.

SLIDE 23
Choi et al.: Active control for drag reduction using (1) v control at the surface with suction and blowing based on detection in the flow of sweep and ejection events, (2) w control at the surface, (3) combinations of the two types of control, etc. The figures show the effects of control compared to no control on TKE production and dissipation rates and on the vorticity component rms distributions.

SLIDE 24
Saddoughi & Veeravalli: Performed a highly regarded experiment in the NASA AMES huge wind tunnel with its 80’ x 120’ test section to examine indicators of local isotropy in turbulent boundary layers. They documented the effects of Reynolds number and proximity to the wall. The figures here show examples of (1) compensated streamwise and cross-stream spectra rather far from the wall and at a
rather high Reynolds numbr (Re₃ = 1450) and (2) compensated second-order structure functions for streamwise and cross-stream velocity fluctuations. Both plots provide evidence of local isotropy under these conditions.

Wallace & Ong: We were kindly allowed to piggyback on their experiment to use our 12-sensor probe to examine local isotropy of the vorticity field. The figure shows evidence of it in the inertial subrange as seen in the ratio of the two cross-stream vorticity components computed from the streamwise component under isotropic assumptions to their measured values. This ratio should be unity for isotropic flow, and it is in the inertial subrange. Experimental error takes over in the dissipation range of this figure.

Mestayer had carried out an earlier and similar study in the high Reynolds number IMST Air-Sea Iteration Simulation tunnel at Re₃ = 616 in the dissipative range but not in the inertial subrange.

Slide 25
Nagano & Tagawa: Trajectory analysis based on uv plane quadrants illustrated in upper left. In lower right the number of types of types of trajectories are shown as a function of the Willmarth & Lu "hole" size. The figure on the right shows auto regressive (AR) model predictions of time series of temperature for various trajectory patterns.

SLIDE 26
Klewicki et al.: Developed field site southwest of Salt Lake City, Utah, on the Salt Flats, where measurements in the atmospheric surface layer could be carried out. At sundown, neutral stability occurs giving conditions similar to those in a laboratory boundary layer but at the very high Reynolds numbers, Re₉, of \(O(10^6)\). The figures show: (1) the histogram of spanwise low-speed stream spacing obtained from flow visualization, (2) distribution of the rms streamwise velocity distribution showing how the peak increases with Reynolds number, (3) the joint pdf of the u and v fluctuations at low and high Reynolds numbers and (4) the space-time auto-correlation of u at low and high Reynolds number.

Folz & Wallace: They have invited many research groups to work there over the years. We were there the first year, and, among other things, measured the contributions of all the terms to the dissipation rate.

SLIDE 27
Jeong et al.: Used method of detecting vortices with -λ₂, the second invariant of the velocity gradient tensor which indicates dominance of rotation over strain. Found quasi-streamwise vortices that are not in the form of hairpins. Vortices, of opposite sign, slightly inclined to the wall and skewed in the x-z plane, exist in staggered overlapping arrays. They state that a phase difference in space accounts for nearly
all of the Q2 and Q4 Reynolds stress as well as counter-gradient Q1 and Q3 Reynolds stress.

Schoopa & Hussain: Carried out a transient growth stability analysis to show how the vortices emerge out of instabilities of low-speed streaks under certain conditions.

SLIDE 28
Honkan & Andreopolous: Used a 12-sensor probe to obtain the angular orientation of the projection of the vorticity vector near the wall in wall normal and wall parallel planes of the flow.

Ong & Wallace: Obtained these orientations for the vorticity filaments that most contribute to the vorticity covariances from weighted vorticity component joint pdfs (covariance integrand plots).

SLIDE 29
Barenblatt et al.: Proposed a Reynolds number dependent power law alternative to the log law to describe the mean velocity in the overlap region. The figure shows many different data sets plotted as evidence to support this theory. The debate about the veracity of this partial similarity law compared to the complete similarity log law still continues.

SLIDE 30
Guarini et al.: Carried out a supersonic Mach 2.5 DNS that showed very little difference from subsonic turbulent boundary layer statistics. The figures show the distributions of the rms vorticity components and the TKE budget.

Kholmyanshy et al.: Carried out a study using a 20-sensor probe to measure both velocity and velocity gradient as well as temperature fluctuations. The measured many different properties of these fields including the joint pdf of the enstrophy production vs. production of strain shown in the figure.

SLIDE 31
Adrian et al.: Used planar PIV in numerous studies to reveal many features of the structure of turbulent boundary layers. Fig. in upper center compares rms spanwise vorticity to DNS and hot-wire values. The figures in the center and on the right show large scale zones of coherent momentum, high shear in ramps inclined to the wall and vortices that are interpreted as “heads” of hairpins. Their hairpin model, like those of others, accounts for Q2 and Q4 Reynolds stress. They also describe the hairpins as occurring in “packets” and account for the creation of new hairpins.

SLIDE 32
Chacin & Cantwell: Used critical point theory, primarily developed by Perry and Chong, to analyse the Spalart turbulent boundary layer DNS. The top middle figure shows regions of postitive discriminant in association with Reynolds stress events.
The top right figure shows the characteristic “tear drop” shape of the Q-R plane joint pdf with superimposed regions of Q2 and Q4 Reynolds stress. The regions in this plane with respect to the Villefosse line of zero discriminant are described by the flow categories in the figure to the lower left.

Andreopolous & Honkan: Obtained this teardrop shape jpdf from 12-sensor hot-wire measurements in the buffer layer of their experimental turbulent boundary layer. It is now believed to be a universal feature of turbulence.

SLIDE 33
Carlier & Stanislas: Used planar PIV to investigate structure in various planes, including planes tilted upstream and downstream across the flow, to study the eddy structure in the boundary layer at \( \text{Re}_\theta = 7,500 \). They used a pattern recognition technique that involved convolving a model vortex with the 2D flow field to educt the actual vortices. Instantaneous and average vortices are shown in the figures in the upper right. They studied Q2 and Q4 events in spatial relationship to these vortices.

SLIDE 34
Kim & Adrian: Observed very large scale motions (VLSMs) in a turbulent pipe flow that were 12 – 14 times as long as the pipe radius.

Del Alamo et al: Also observed these VLSMs in their channel flow DNS.

Hutchins & Maurusic: Observed VLSMs as long as \( 20 \delta \) in the log and lower wake regions in their experiment in the Utah desert, and studied how they affect premultiplied 1D spectra of the streamwise velocity fluctuations. The rising plateau in the rms distribution further from the wall is related to the second peak in the spectrum coming from these VLSMs.

SLIDE 35
Ringuette et al.: Carried out a DNS at \( \text{Re}_\theta \approx 2600 \) and Mach \( \approx 3 \) in which they observed most of the same types of structures as in subsonic flow.

Pirozzoli et al.: Also carried out a supersonic DNS at Mach = 2 and \( \text{Re}_\theta = 950 – 1350 \). They studied the statistical properties of quasi-streamwise vortices near the wall and of hairpins and hairpin packets further from the wall. In the outer layer they state that these statistical properties are consistent with noninteracting closed loop vortices. In their later study they conclude that sheet-like structures have a greater influence on the statistical properties of the TBL than the vortices.

SLIDE 36
Mathis et al.: Studied the modulating effect that large scale motions in the outer flow have on the fluctuations in the inner region of the flow. They did this by filtering the streamwise velocity signals and correlating them. They examine how the degree of correlation depends on wall normal distance and how it is related to the 1D spectra.
SLIDE 37
Wu & Moin: Carried out a spatially developing DNS of the TBL which goes through bypass transition to turbulence. It exhibits a forest of hairpins. When the wall is passively heated, the temperature field also exhibits hairpins.

SLIDE 38
Sheng et al.: Used digital holography to study the wall layer structure in a square duct at Reₜ = 1470 and obtained conditionally averaged hairpin structures that emerge from the spanwise vorticity sheets near the wall and are related to high wall shear stress occurrences.

Elsinga et al: Found hairpin packets using tomographic PIV at Re₀ = 34,000 and Mach = 2

SLIDE 39
Schlatter et al.: Carried out boundary layer DNS up to Re₀ ≈ 4,300. They carefully studied statistical properties, and have also compared the consistency of various DNS studies. They don’t observe hairpins in their highest Reynolds number DNS.

SLIDE 40
Jimenez et al.: Carried out a TBL DNS up to Re₀ = 2100. They don’t observe hairpins, but they do observe the large scale coherent momentum events.

SLIDE 41
Guala et al.: Observations in the atmospheric surface layer quantifying interactions between the VLSMs and the turbulence from the energy containing to the dissipative scales.

Duan et al.: DNS of TBL up to hypersonic cases. Flow structure doesn’t change much.

SLIDE 42
Park et al.: Showed that statistics, including those of the fine scale properties, enstrophy and dissipation rate, are very similar in transitional turbulence spots and in developed turbulence. This implies that the structure is likely to be similar. Octant analysis showed that motions consistent with mean gradient transport of momentum and heat are the dominant contributors to the fluxes for both transitional spots and developed turbulence. The transport of momentum and heat is strongly associated with vortices as shown in the cross-stream cuts through the instantaneous fields for the transition and developed cases.

SLIDE 43

Summary
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(send additions to wallace@umd.edu)

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