EVIDENCE FOR THE PERSISTENCE OF HAIRPIN FOREST IN TURBULENT, ZERO-PRESSURE-GRADIENT FLAT-PLATE BOUNDARY LAYERS

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ABSTRACT

We report well-resolved flow visualization results obtained from very-large-scale direct numerical simulation (VLS DNS) of a nominally zero-pressure-gradient, smooth, incompressible, flat-plate boundary layer (ZPGFPBL). The momentum-thickness Reynolds number develops continuously from 80 to approximately 2000. A unique aspect of the present VLS DNS study is its strong connection and remarkable consistency with the large body of classical ZPGFPBL experimental visualization work that began in the late 1950s, peaked in the early 1980s and still somewhat active until this day. Our VLS DNS results demonstrate, beyond reasonable doubt, a preponderance of hairpin vortices in ZPGFPBLs upto momentum-thickness Reynolds number 2000.

INTRODUCTION

A standard boundary layer is a ZPGFPBL with infinitesimal disturbances in the sense of Schubauer and Skramstad (1947). A quasi-standard boundary layer is a nominally ZPGFPBL with finite but weak free-stream or other types of imposed perturbations. They are the fundamental compoent of aeronautical fluid mechanics. As such, scientists and engineers are interested in the kinematics and dynamics of organized, large-scale vortex structures in the ZPGFBPL. During the 30 years from Theodorsen (1952) to Head and Bandyopadhyay (1981) significant progresses were achieved in this field by world-renowned experimental groups, mostly using various flow visualization techniques: Kline et al (1967), Rao et al (1971), Blackwelder and Kaplan (1976), Falco (1977), Brown and Thomas (1977), Praturi and Brodkey (1978), among many others. These landmark experimental visualization results were sumarized in Cantwell (1981), Hussain (1983). Robinson (1991) also reviewed those early experimental papers, but his review and comments casted significant doubts on the model of Theodorsen (1952), Head and Bandyopadhyay (1981) in ZPGFPBLs.

More recent experimental work on the ZPGFPBL structure rely upon planar PIV technique: Adrian et al (2000), Ganapathisubramani et al (2003), Hutchins and Marusic (2007), among many others. These were summarized in Smith et al (1991), Adrian (2007), Wallace (2009). One recent remarkable low-Reynolds number flow visualization study on the ZPGFPBL was published by Delo, Kelso and Smits (2004) who demonstrated a strong agreement with the earlier work of Praturi and Brodkey (1978). Although the current focus of many ZPGFPBL studies are on the existence and mechanism of very-large-sale motion (VLSM), e.g., Marusic et al (2010), we are of the opinion that the more basic question regarding the kinematics and dynamics of large-scale motion (LSM) in the ZPGFPBL has not been fully understood. For example, it is now generally accepted within the turbulence and boundary layer community that hairpin vortices, as initially conceptualized by Theodorsen in the 1950s, could be found in the ZPGFPBLs. However, debate centers on the question whether such hairpin vortices can be considered as the representative, dominating vortex structure within LSMs in the ZPGFPBL (Marusic 2009, Schoppa and Hussain 2002). In other words, is their occurrence merely a rare event? Can they be easily detected from the layer or great effort has to be devoted in order to just find one such vortex from a ZPGFPBL? This controversy persists primarily because majority of the previous direct numerical simulation (DNS) results on the ZPGFPBL, e.g., the analysis of Robinson (1991) on the data of Spalart (1988), fail to reveal the anticipated dominance of hairpin vortices. For example, it was concluded by Robinson that “low-Reynolds-number numerical simulations show vortices in the shape of complete loops or horseshoes to be rare, although elements of these vertical structures are common”. The uncertainty is amplified further since several DNS studies reported within the past year (Schlatter et al 2009, Lee and Sung 2011, Araya et al 2011), except for those of Wu and Moin (2009a,b, 2010), Wu (2010), on ZPGFPBLs do not report the preponderance of hairpin vortices.

SIMULATION AND RESULTS

Figures 1 to 4 present iso-surfaces of the second invariant of the velocity gradient tensor at one random instant obtained from the ZPGFPBL. The simulation itself is fully described in Wu and Moin (2010). The statistics agree with classical experimental data, e.g., DeGraaff and Eaton (2000). Each figure covers approximately a stream-wise range 500 of momentum-thickness Reynolds number. The iso-surfaces in the figure are at a uniform value colored based upon local values of with values larger than 300 wall-units being represented by red. The entire flow field can not be drawn into a single frame because the memory limitation of our local work-station. Figures 1 and 2 cover the transitional region, whereas Figures 3 and 4 correspond to turbulent boundary layer region. Although more chaotic in the turbulent region, numerous hairpin vortices are readily detected using this approach in both the near-wall and outer regions of the boundary layers. This suggests that the hairpin vortices in the higher Reynolds number region of Figure 4 are not simply the aged hairpin forests convected from the upstream transitional region of Figure 3. Overall, these images provide un-precedent, strong and compelling evidence for the preponderance of hairpin vortices in the first ZPGFPBL.

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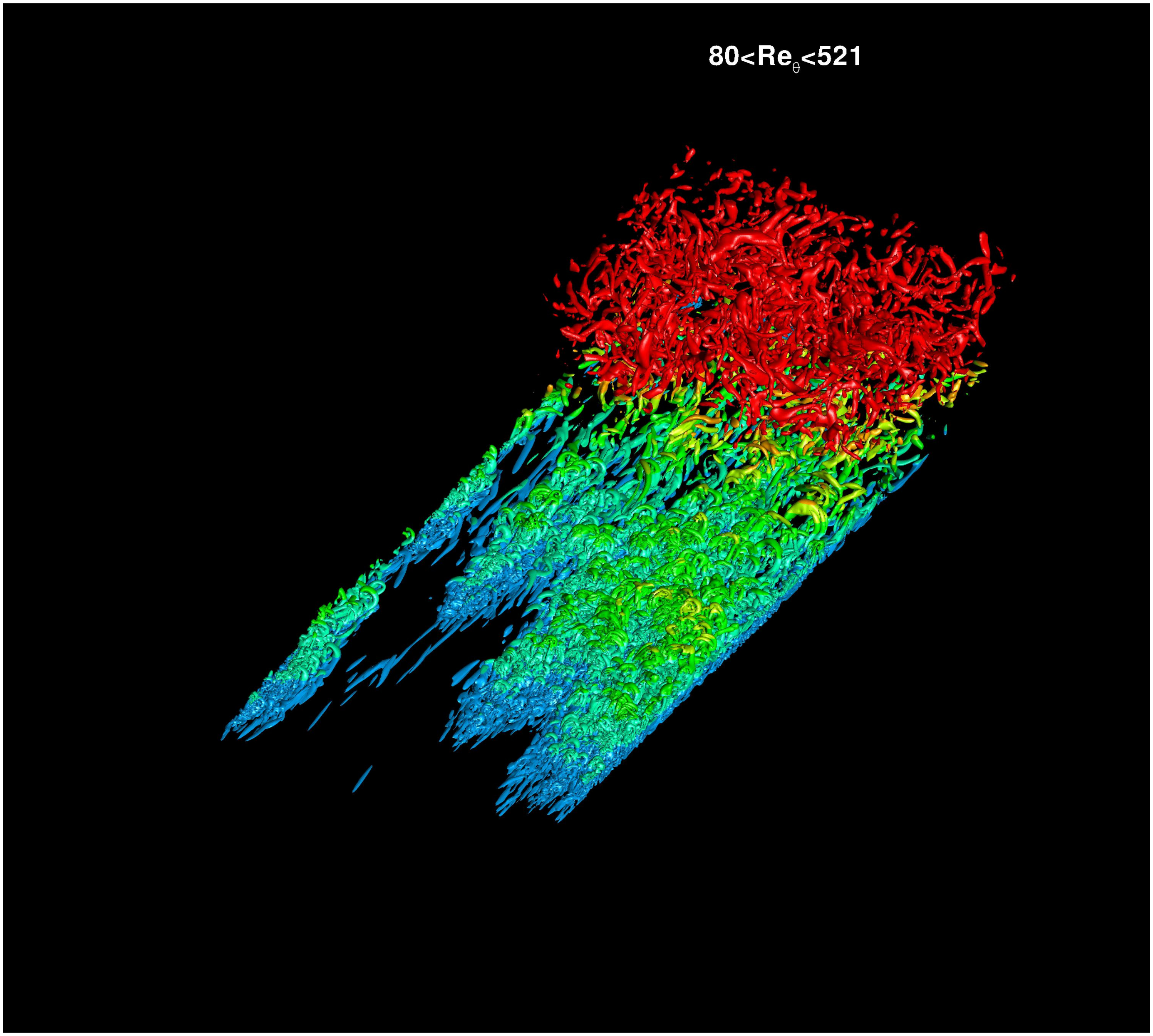

Figure 1. Iso-surfaces of the second invariant of the velocity gradient tensor at one instant for the first ZPGFPBL with free-stream isotropic turbulence blocks over the turbulent region of $80 < \mathrm{Re}_\theta < 521$. The iso-surfaces are colored based on local values of y^+ with values larger than 300 wall-units being represented by red. Note only a small segment of the entire flow field is shown.

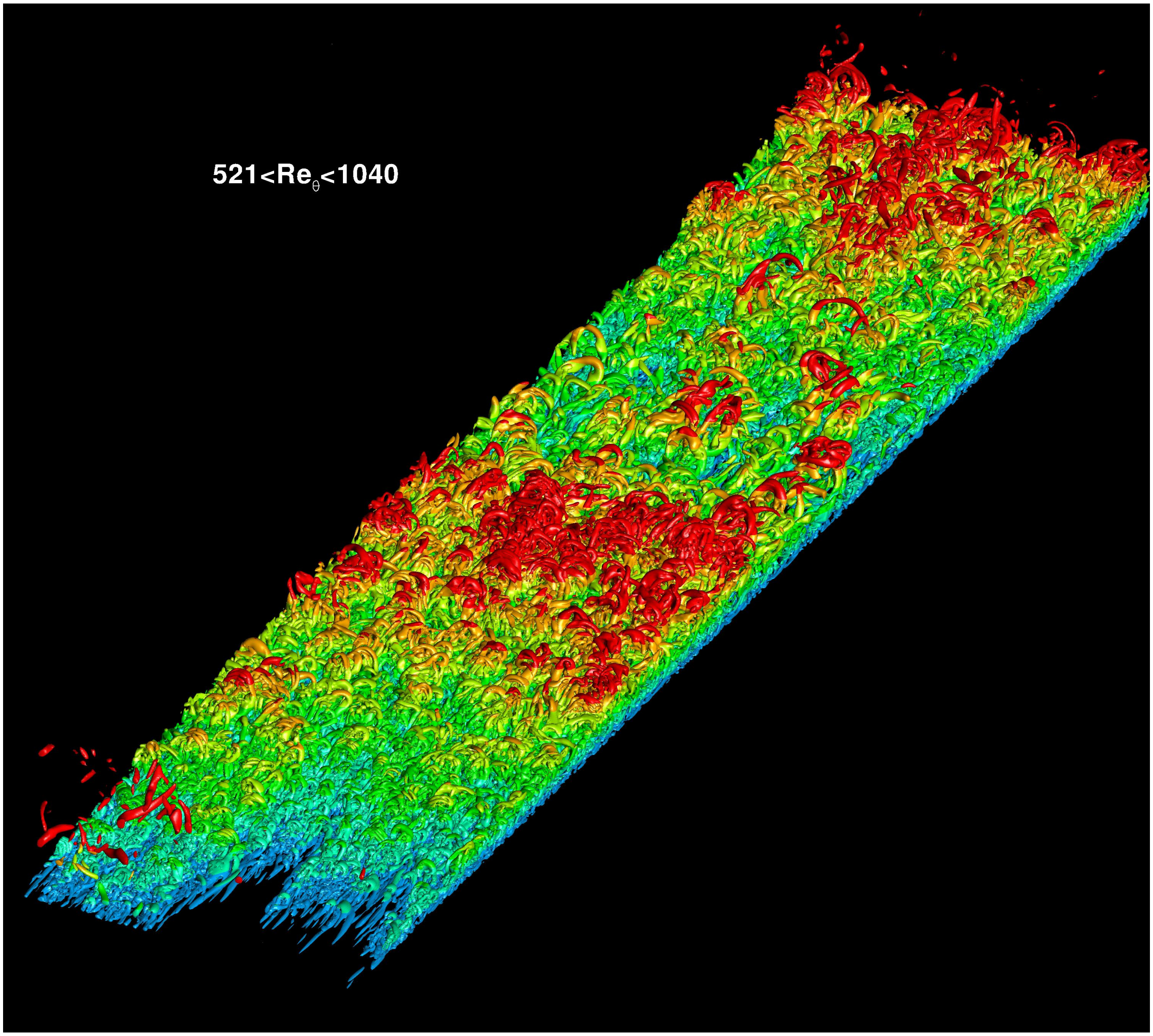

Figure 2. Iso-surfaces of the second invariant of the velocity gradient tensor at one instant for the first ZPGFPBL with free-stream isotropic turbulence blocks over the turbulent region of $521 < \mathrm{Re}_\theta < 1040$. The iso-surfaces are colored based on local values of y^+ with values larger than 300 wall-units being represented by red. Note only a small segment of the entire flow field is shown.

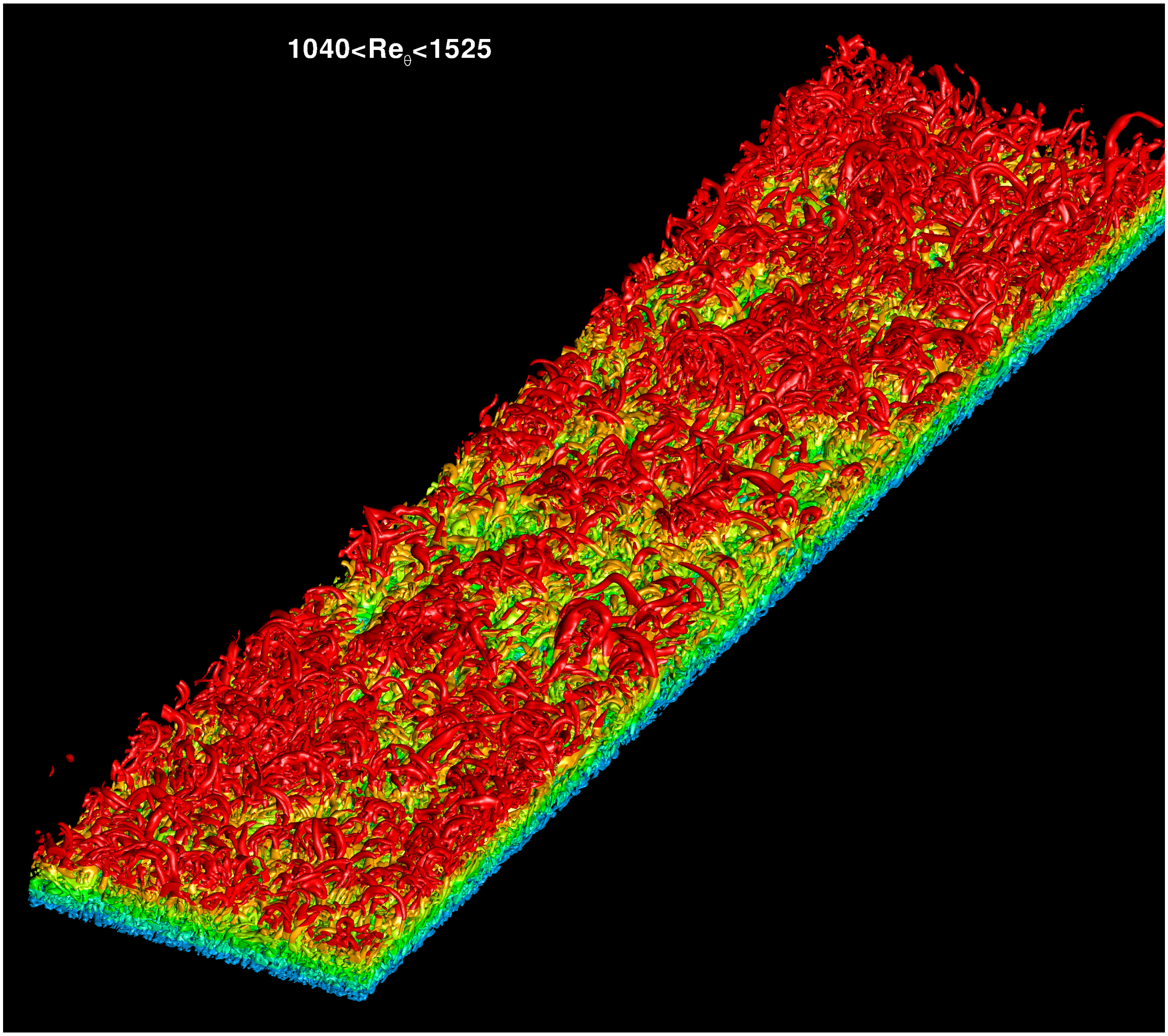

Figure 3. Iso-surfaces of the second invariant of the velocity gradient tensor at one instant for the first ZPGFPBL with free-stream isotropic turbulence blocks over the turbulent region of $1040 < \mathrm{Re}_\theta < 1525$. The iso-surfaces are colored based on local values of y^+ with values larger than 300 wall-units being represented by red. Note only a small segment of the entire flow field is shown.

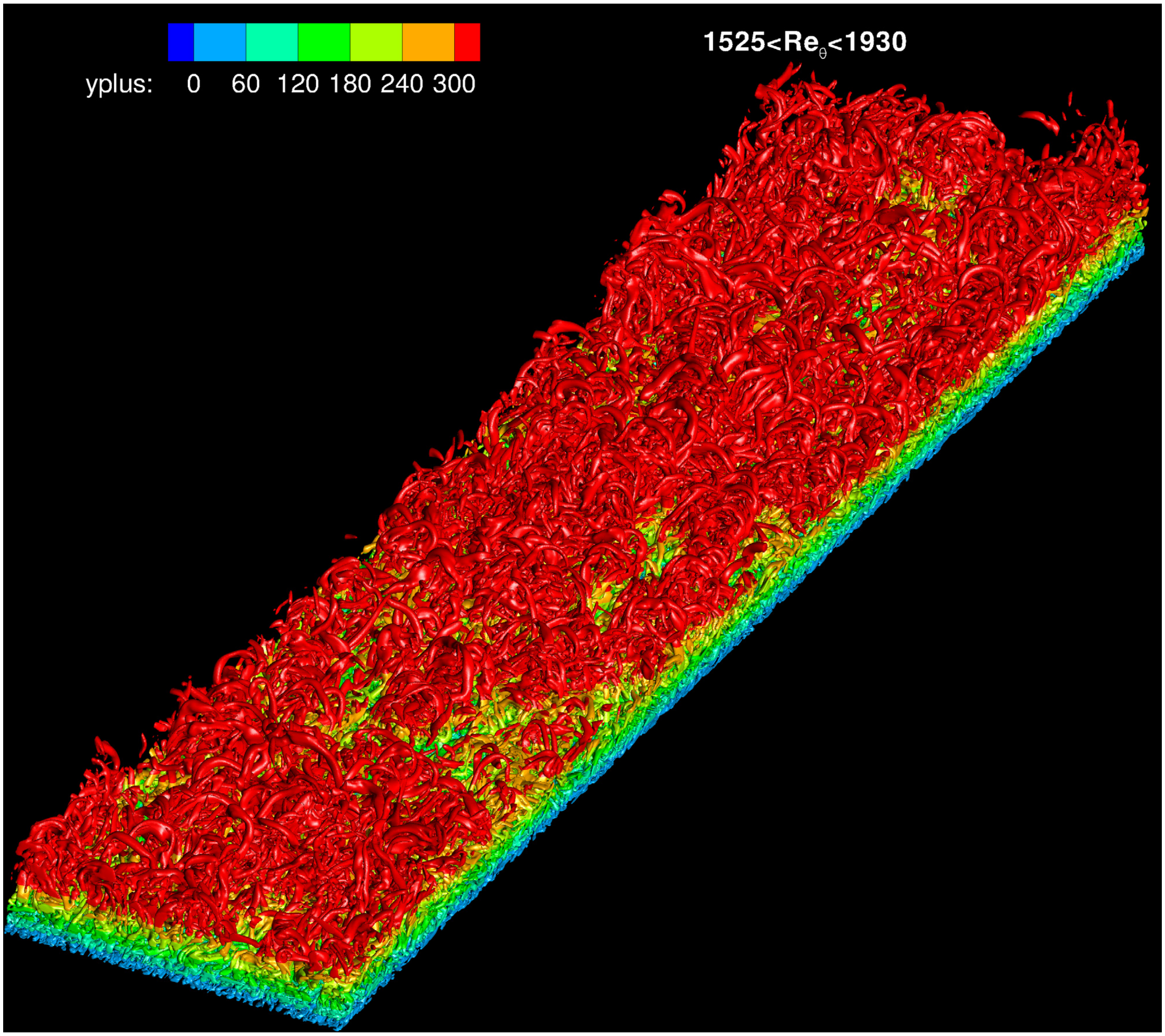

Figure 4. Iso-surfaces of the second invariant of the velocity gradient tensor at one instant for the first ZPGFPBL with free-stream isotropic turbulence blocks over the turbulent region of $1525 < \mathrm{Re}_\theta < 1930$. The iso-surfaces are colored based on local values of y^+ with values larger than 300 wall-units being represented by red. Note only a small segment of the entire flow field is shown.