Simulations Of Turbulence Transition In Long Pipes

A numerical investigation of transition from turbulent to laminar flow in long pipes

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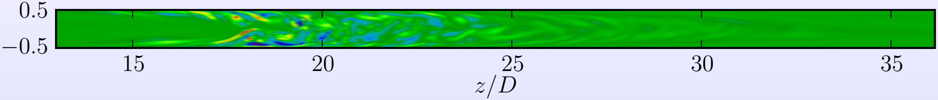
Introduction

- Instability in pipe flow has been an outstanding problem in fluid dynamics over the past century -- first observed by Reynolds in his paper of 1883, where he defined the Reynolds number, Re.
- Previous papers on the transition problem have mainly concentrated on transition from **laminar to turbulent** flow. We wish to build a phase portrait of the fluid going from **turbulent to laminar** flow, and investigate states of **laminar-turbulent co-existance**.
- This talk outlines initial results that we have obtained from direct numerical simulations (DNS) of the pipe flow problem at transitional Reynolds numbers.
- None of these simulations would have been possible without the computing resources at the Centre for Scientific Computing, University of Warwick. (We use a recently built 960-core machine using 3GHz Intel Xeon processors.)

Large-scale structures

- For $1900 \leq \mathrm{Re} \leq 2200$, we observe *puffs* in the fluid. These turbulent structures co-exist with laminar flow and propagate down the length of the pipe.



- This puff was recorded at $\mathrm{Re} = 2000$ and has length $L \approx 25D$, so larger lengths are needed to capture their behaviour.

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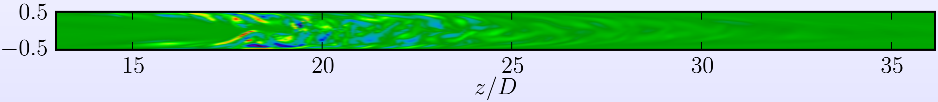
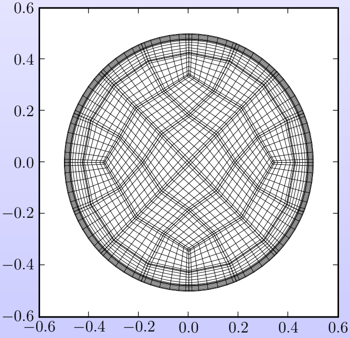


- This puff was recorded at $\mathrm{Re} = 2000$ and has length $L \approx 25D$, so larger lengths are needed to capture their behaviour.
- Because correctly resolved DNS is computationally expensive, most turbulence simulations use short pipes. The most recent numerical simulations of these structures have been in a pipe of length $L = 16\pi D \approx 50D$ [Pringle & Kerswell, *PRL*, 2007].
- Experimental pipes can be several hundred diameters long [Darbyshire & Mullin, *JFM*, 1995]. Thanks to Moore's law, we can now begin to study these pipe lengths using DNS.

DNS Techniques

- Our simulations use an existing DNS code, Semtex [Blackburn & Sherwin, *J. Comput. Phys.*, 2004].
  - Spectral-element discretization in circular cross-sections.
  - Fourier pseudo-spectral down length of pipe with periodic boundary conditions.
  - Parallelized using MPI.
- Although the problem is a natural choice for a cylindrical-polar co-ordinate system, we use a Cartesian geometry for finer control over the placement of data points in circular cross-sections.



Simulations

- Parameters for the simulations were:

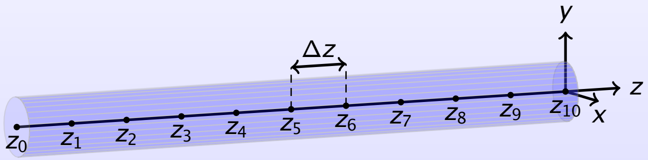
L	$16\pi D \approx 50D$	$48\pi D \approx 150D$
N_z	768	2048
Re	$1900 \leq \mathrm{Re} \leq 2150$	$2100 \leq \mathrm{Re} \leq 2200$
Δt	2×10^{-3}	2×10^{-3}

- The flow is driven using a constant volumetric flux $q = 1$ through a circular cross-section of the pipe.
- The simulation is started with uniform turbulence using a short run at $\mathrm{Re} = 5000$. We then reduce Re as follows:

$5000 \to 4000 \to 3000$	500 time units
$2800 \to 2650 \to 2500 \to 2350$	1000 time units
$2200 \to 2150 \to 2100 \to 2050 \to \cdots$	2000 time units

History Plots

- Field data is too large to record regularly. Instead we measure *history data*: every 0.1 time units, we record velocity field data along the axis of the pipe.



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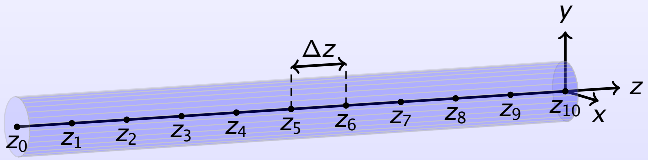


- For the velocity field $\mathbf{u} = (u, v, w)$, we construct the quantity

$$q(z,t) = \sqrt{u^2 + v^2}\Big|_{(x=0,y=0,z,t)}$$

and then change to a moving frame of reference by applying

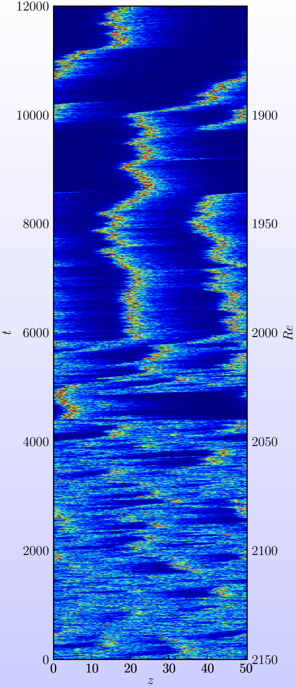
$$q(z,t) \to q(z - ct, t)$$

where c is, for example, the speed of a puff.

- This data produces a space-time contour plot which is useful for analysing general qualities of the fluid.

$L = 50D$ History Data

- $1900 \leq \mathrm{Re} \leq 2150$.
- $0 \leq t \leq 12000$.
- Re-laminarization occurs at $\mathrm{Re} = 1750$.
- The data took roughly 4.1 CPU years to generate.



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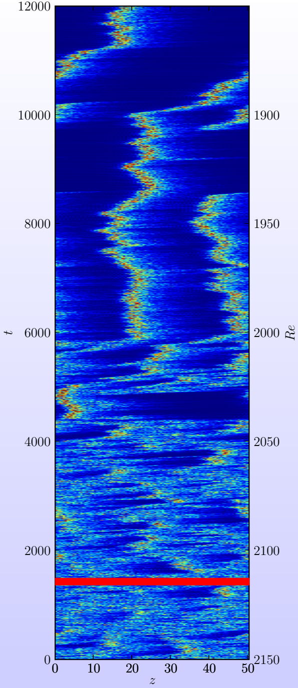
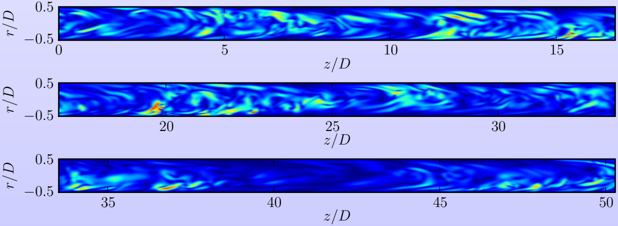


$\mathrm{Re} = 2150, t = 1500$



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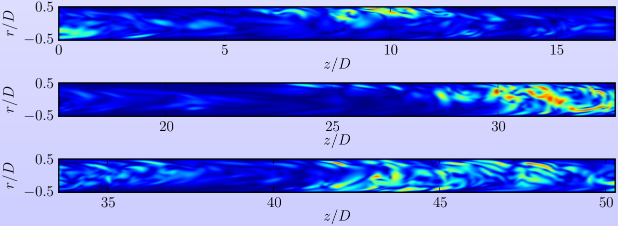
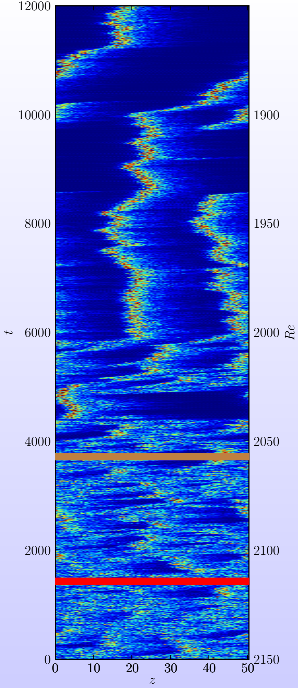
$\mathrm{Re} = 2100, t = 3900$





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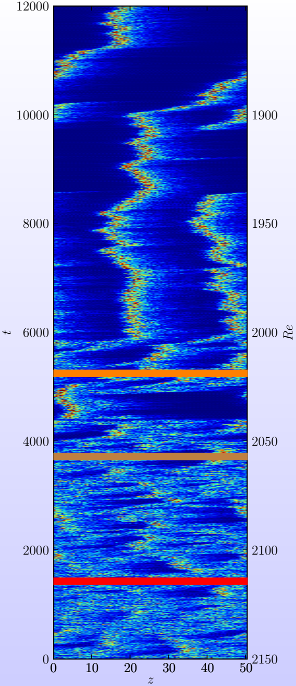
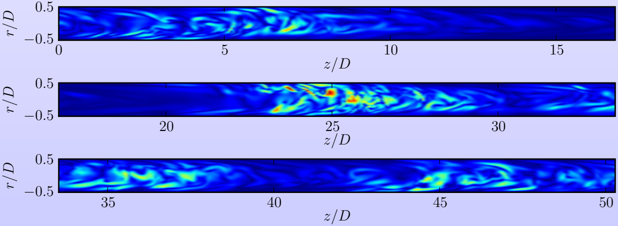


$\mathrm{Re} = 2050$, $t = 5400$



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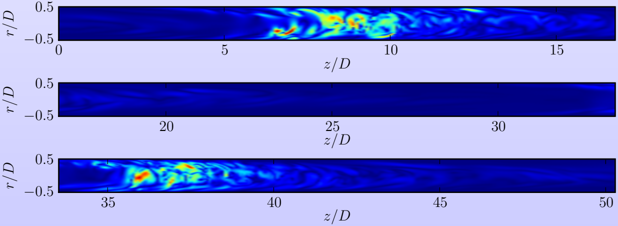
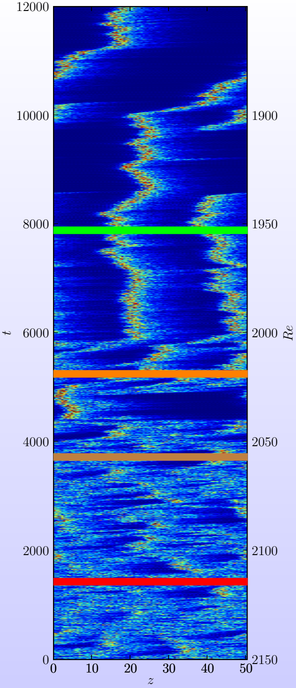
$\mathrm{Re} = 2000$, $t = 7950$





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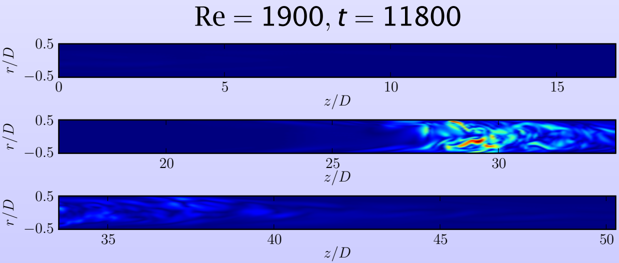
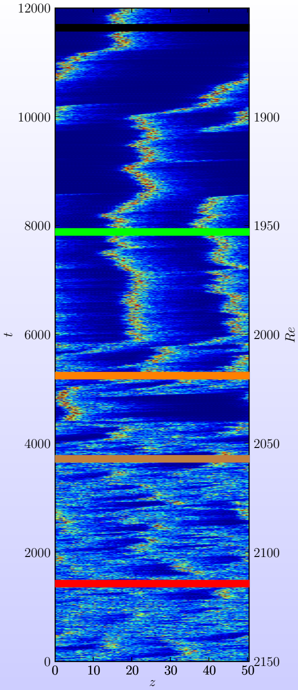
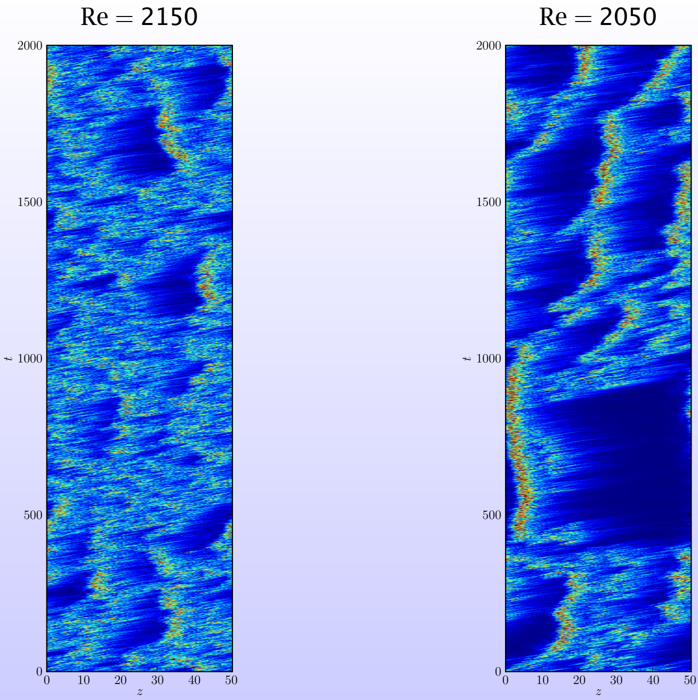
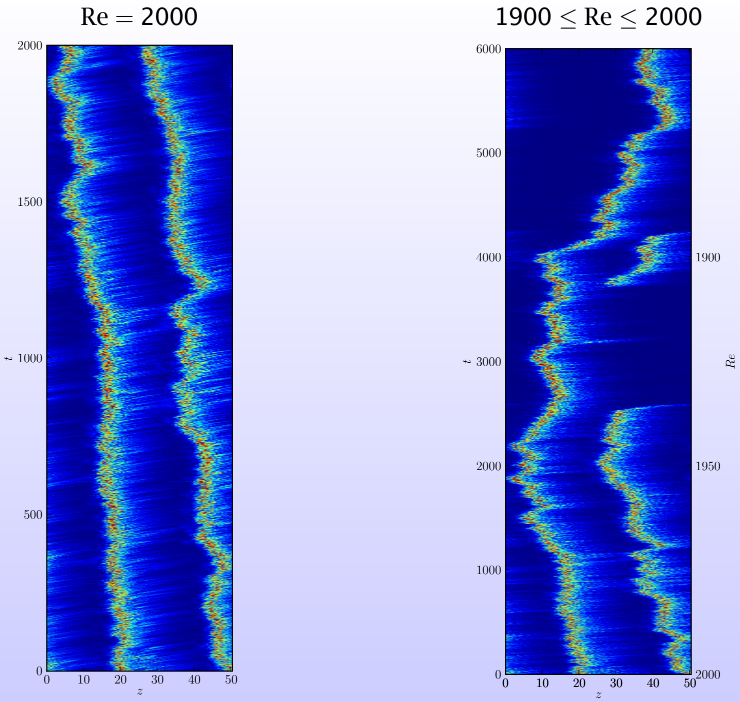
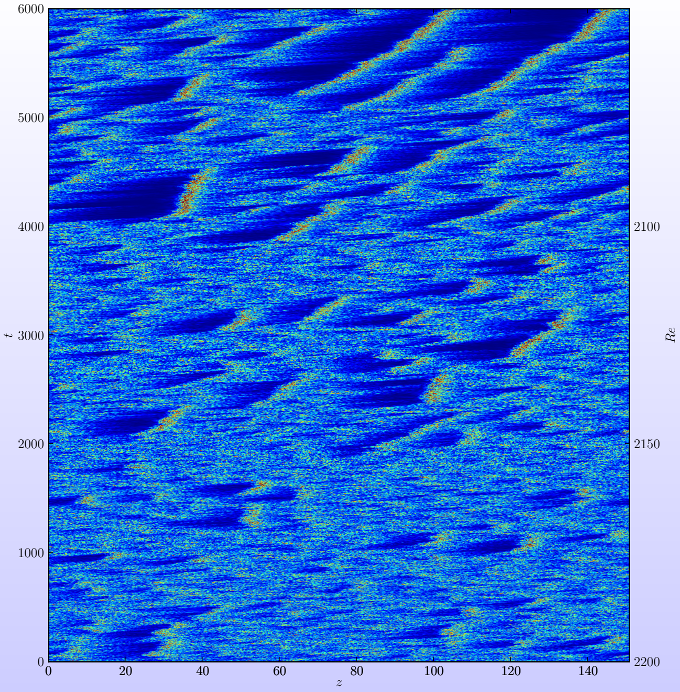





Re = 2150
Re = 2050
t
z
0
500
1000
1500
2000
0
10
20
30
40
50


Re = 2000
1900 ≤ Re ≤ 2000
t
z
Re
0
500
1000
1500
2000
10
20
30
40
50
3000
4000
5000
6000
1900
1950



6000
5000
4000
3000
2000
1000
0
t
0
20
40
60
80
100
120
140
z
2100
2150
2200
Re

Summary and Future Work

- Full DNS of pipe flow at transitional and turbulent Reynolds numbers is now possible for lengths $\geq 100D$.
- Although these are initial results, history plots show that puffs are found in the transition from turbulent to laminar flow, and multiple puffs are observed for the $L = 50D$ case.
- Investigate periodicity of puffs: for a single puff of length $L = 25D$, will extending the pipe length cause the puff to 'split' into two puffs?
- Perform a comparison between the results of the $L = 150D$ and $L = 50D$ cases, and see if similar behaviour is observed (especially in relation to any multiple-puff states).
- Simulations in pipes of length $L = 400 - 500D$?