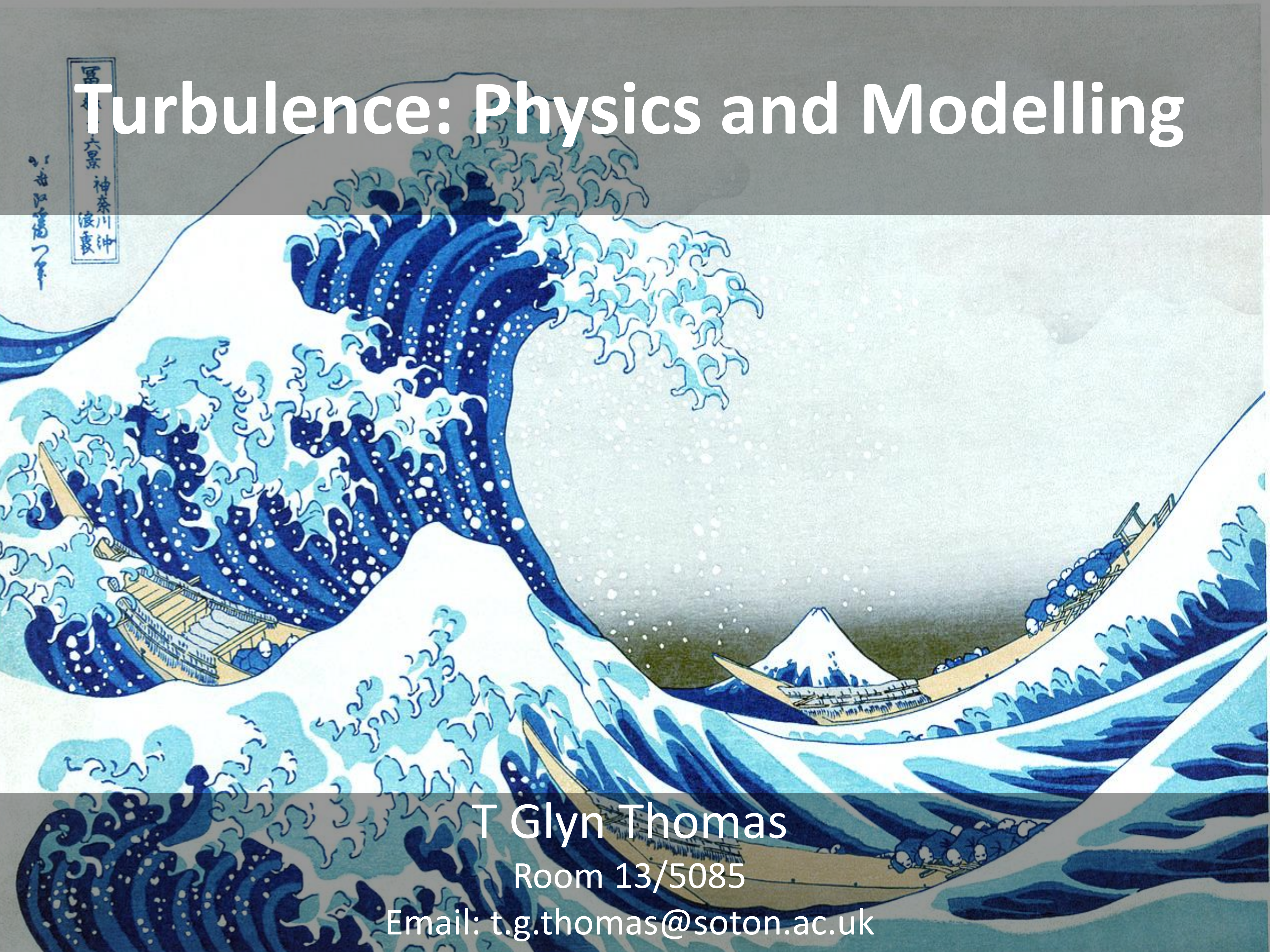
Turbulence: Physics and Modelling



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SESA6061
Turbulence: Physics and Modelling

Focus: Physics of incompressible turbulent flows and strategies available to address turbulence closure problem

Key outcome:
-Insight in to the nature of turbulence
-Knowledge of tools and concepts used for its analysis

Useful texts:
- Turbulence for the 21st Century, W. K. George (http://turbulence-online.com)
- Pope, Cambridge University Press
- Tennekes and Lumley, MIT press
- Davidson, Oxford University Press
- D C Wilcox: *Turbulence Modeling for CFD,* 2nd ed., DCW Industries, 1998
- R. Pletcher, J. Tannehill, D.Anderson, Computational fluid mechanics and heat transfer, CRC Press, 2012

House-Keeping

Assessment (15 Credits):
70% from 2 hour exam
15% coursework on processing turbulence data
15% coursework on numerical modelling project

Three lectures a week throughout (36 lectures in all)

First 12 lectures on turbulence tools and theory
Next 16 lectures on numerical modelling
Final 6 lectures on miscellaneous/recent advances/revision

Monday 11:00-12:00 in 06/1081 L/R B
Tuesday 14:00-15:00 in 06/1129 L/R F
Friday 10:00-11:00 in 59/1257

Turbulence Tools & Theory

The nature of turbulence
Its origin - stability
Mean and fluctuation quantities
General features and major effects

Tools for studying turbulence
Definitions: stationarity and ergodicity
Statistical tools:
Amplitude statistics: probability density function and moments
Time-domain statistics: correlation and spectral functions.

Equations and scales of motion
Reynolds averaging; momentum and Reynolds stress equations
Turbulence energy equation
Transport, Production and Dissipation of kinetic energy including
Kolmogorov’s hypothesis

Numerical Approaches to Turbulence

Computational strategies: hierarchy of turbulence closures
Engineering/CFD models: RANS schemes
'Numerical experiments': DNS and LES
Hybrid RANS/LES: DES
Survey of relevance and limitations

Reynolds-Averaged Navier-Stokes (RANS) models
Motivation, philosophy, and classification
Modelling canonical flows: Homogeneous isotropic turbulence, 2D wall layers
Industrial models:
Complex geometry, pressure gradients/separation, surface roughness,
mean three-dimensionality, compressibility
Eddy-viscosity/Boussinesq closures:
Algebraic/zero-, one- and two-equation models
Example: Spalart-Allmaras one-equation scheme
Limitations of eddy-viscosity closures
Guidelines for CFD users

Direct Numerical Simulations (DNS)
Numerical issues:
Domain size, resolution requirements
Spectral and high-order finite-difference methods
FFTs, aliasing, modified wavenumber analysis
Examples of classical and recent simulations:
plane-channel, 2D and 3D turbulent boundary layers
separation bubbles, shock-boundary layer interaction
Recent developments:
Inflow treatments, and immersed-boundary techniques

Large Eddy Simulations (LES)
Implicit and explicit filtering; subgrid-scale (SGS) modelling
Recent developments: dynamic modelling, approximate deconvolution
Inherent limitations of LES

New Frontiers + Miscellaneous

New frontiers
Unsteady RANS
Hybrid RANS/LES methods

Mean-flow similarity
Self-preserving jets, wakes and mixing layers

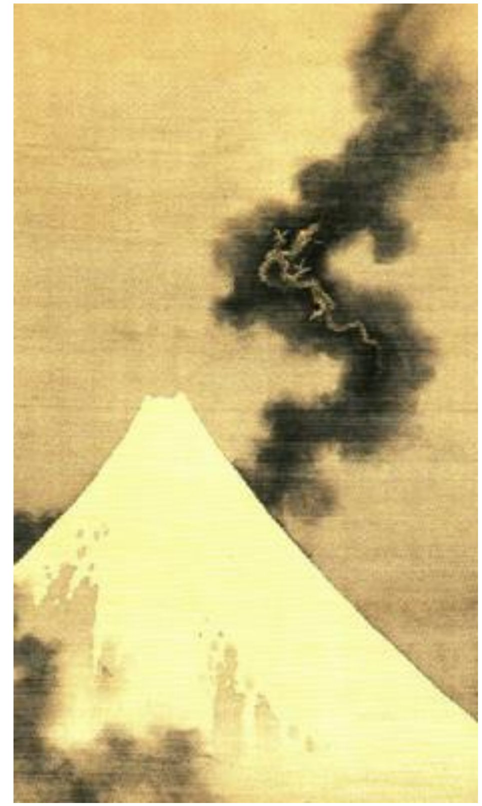
Fine-scale features
Vorticity and enstrophy; vortex stretching
Invariants of velocity gradient tensor

Modal decomposition of turbulent flows
Proper orthogonal decomposition

Revisions (2 lectures)

Turbulence

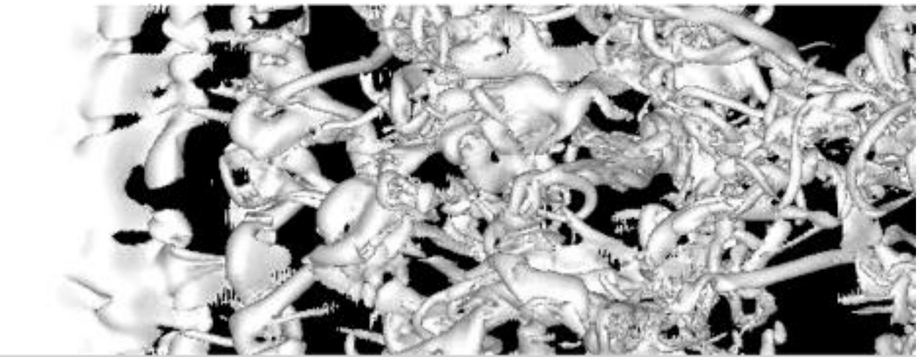
The Great Wave off Kanagawa c1830

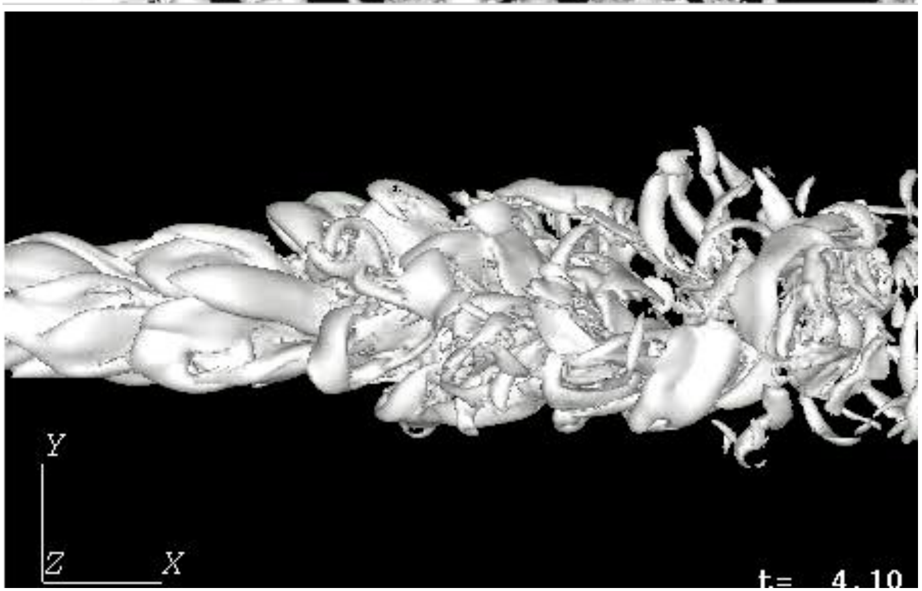


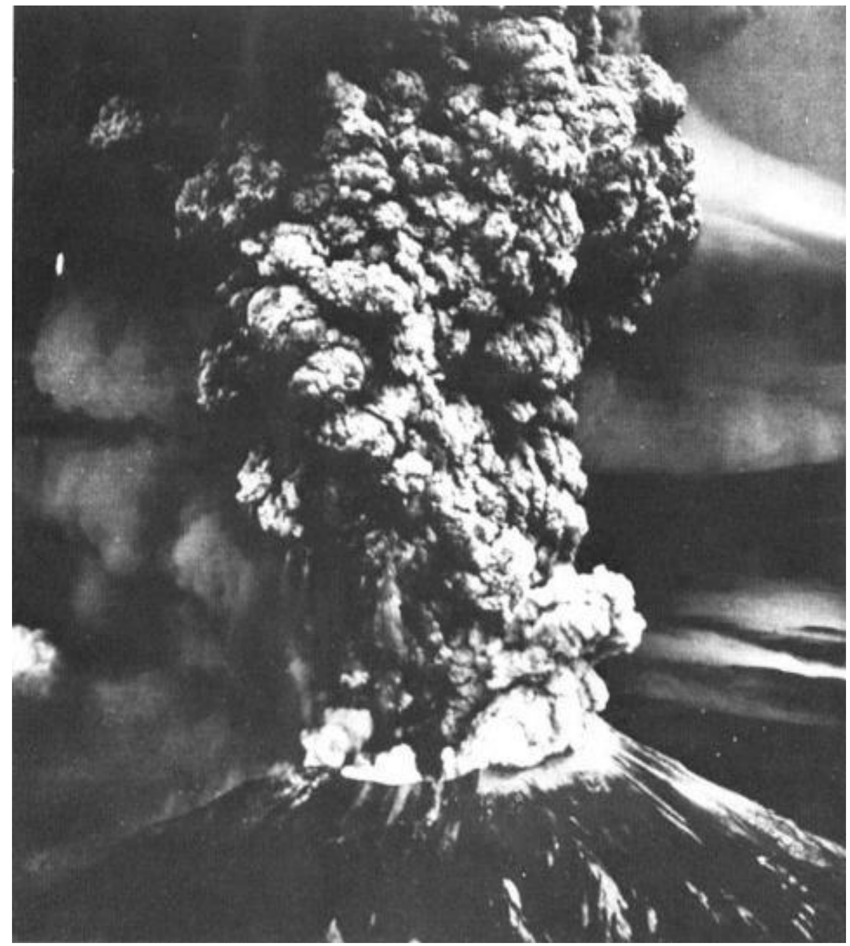
The Dragon of Smoke Escaping from Mt Fuji.

Shear-Generated Turbulence

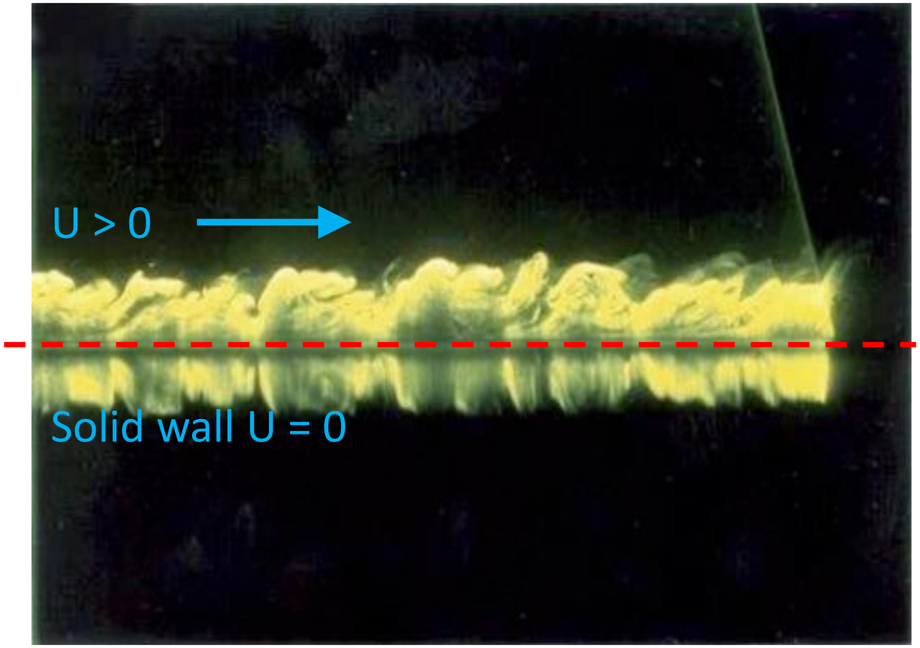
Flow speed difference across a thin sheet => unstable => turbulence structure







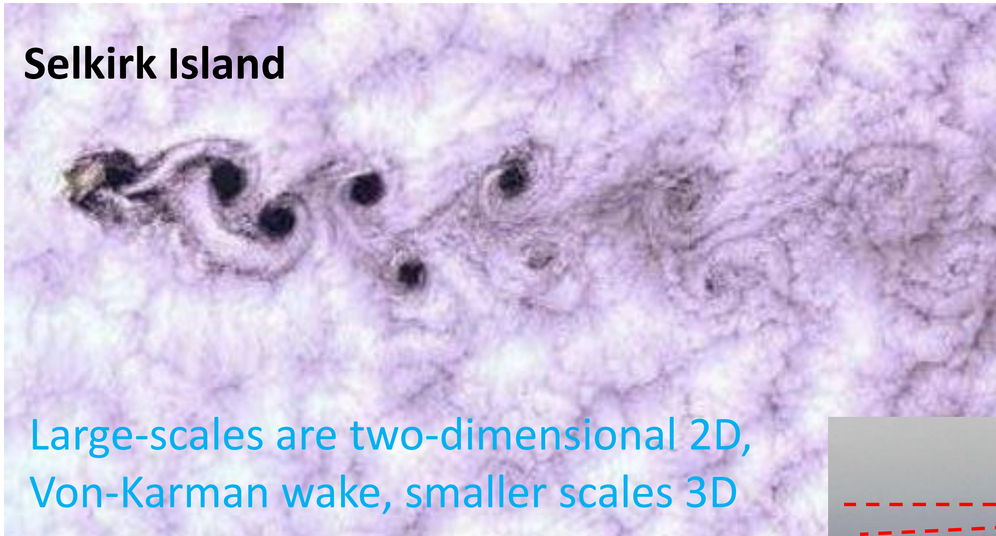
Wall-bounded Turbulence

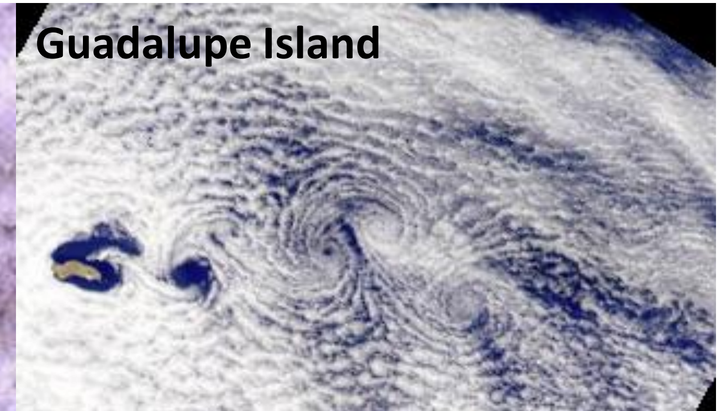


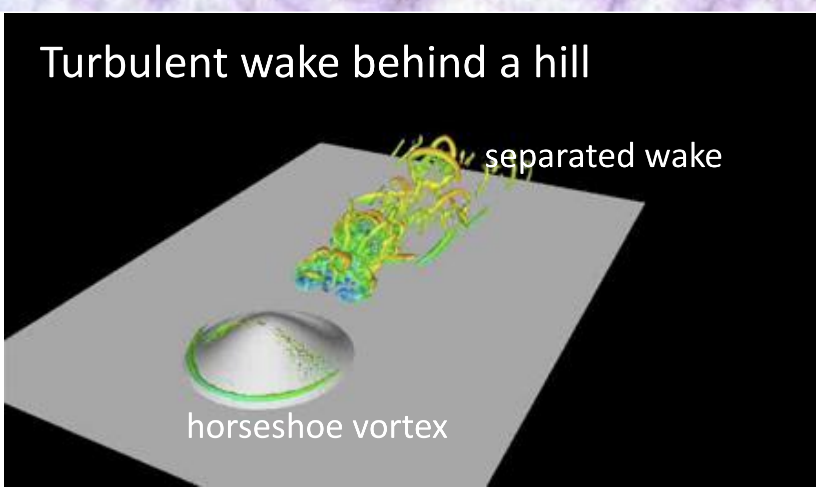
Fluid attaching to solid boundary creates Shear + shear leads to instability.

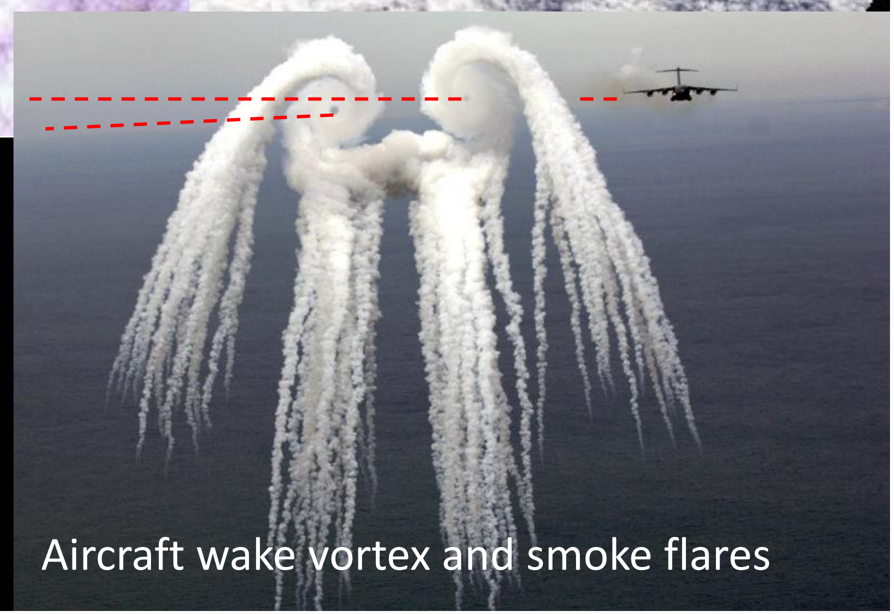
Note the widely-spaced long streaks in this turbulent boundary layer flow over water + waves.

Wake-Generated Turbulence



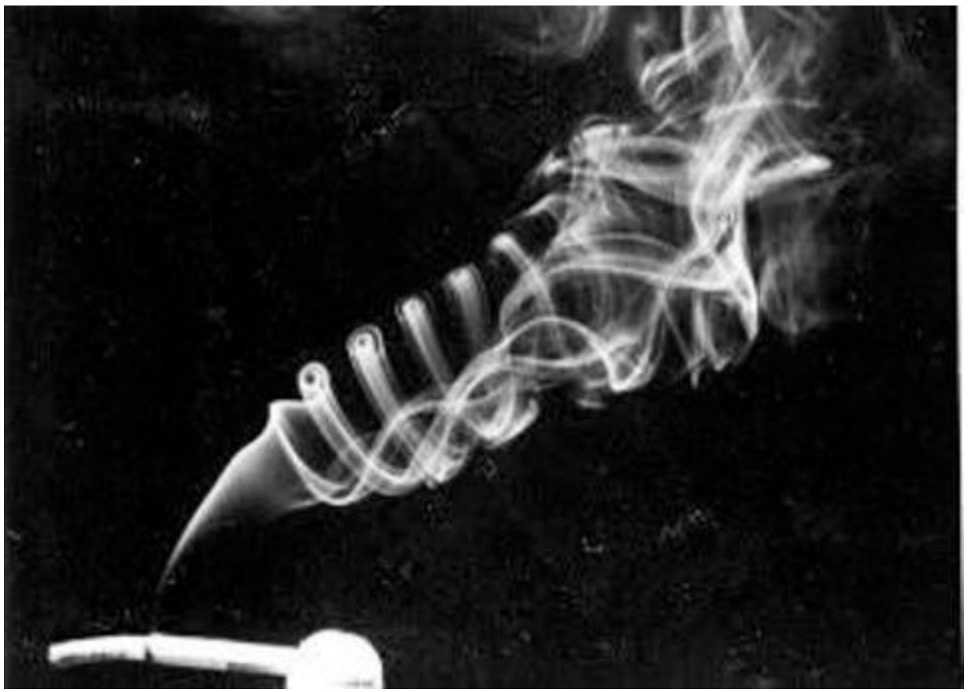




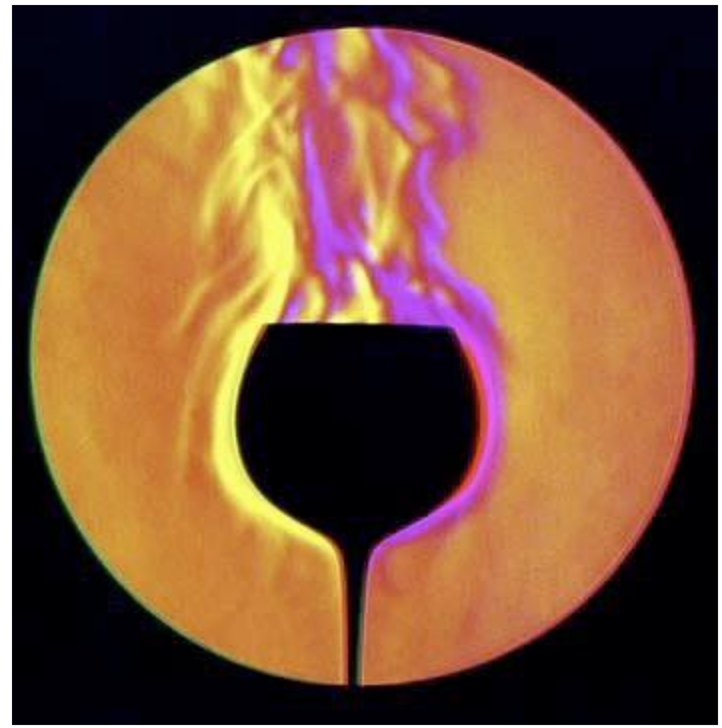


From: G. Fishpool & M. Leschziner

Buoyancy-generated turbulence

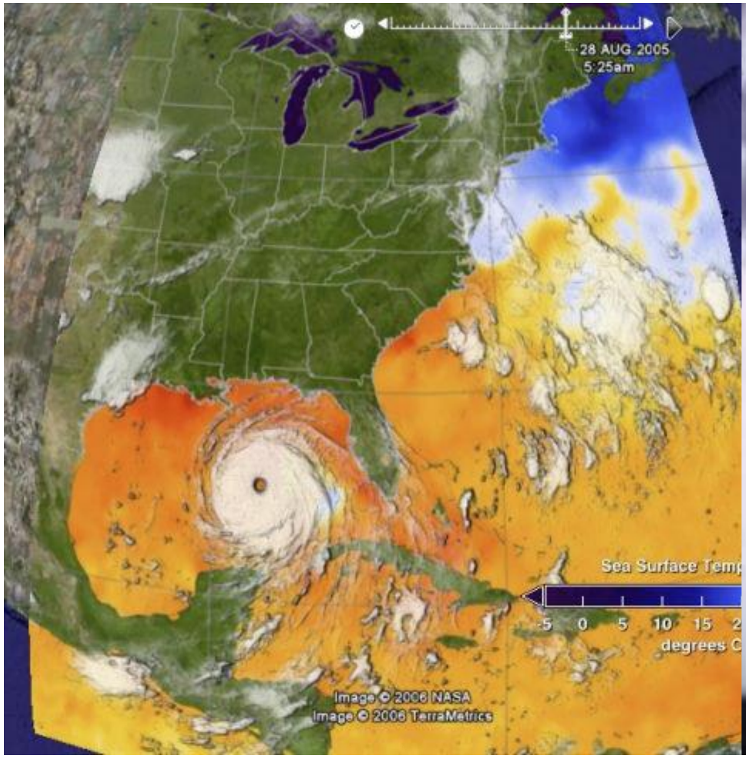


Buoyant jet in a cross-flow. Roll-up of initial shear layer into discrete vortices, axial vortices, thermal plume – complex flow.



Thermal convection, buoyancy driven boundary layer around glass and separated wake above

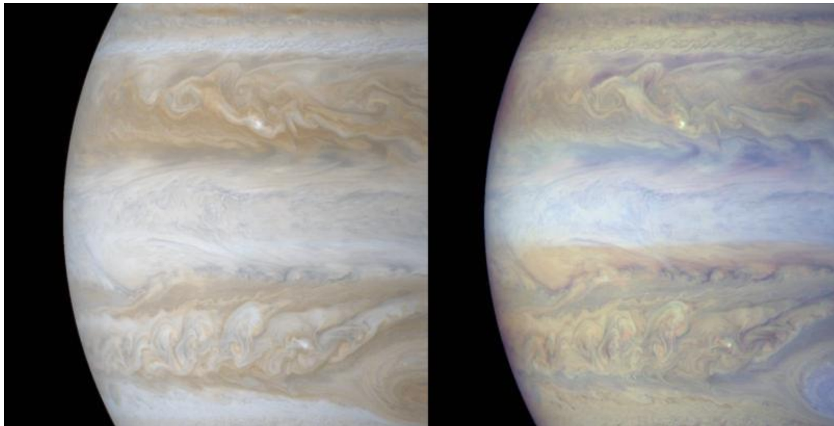
Atmospheric Turbulence

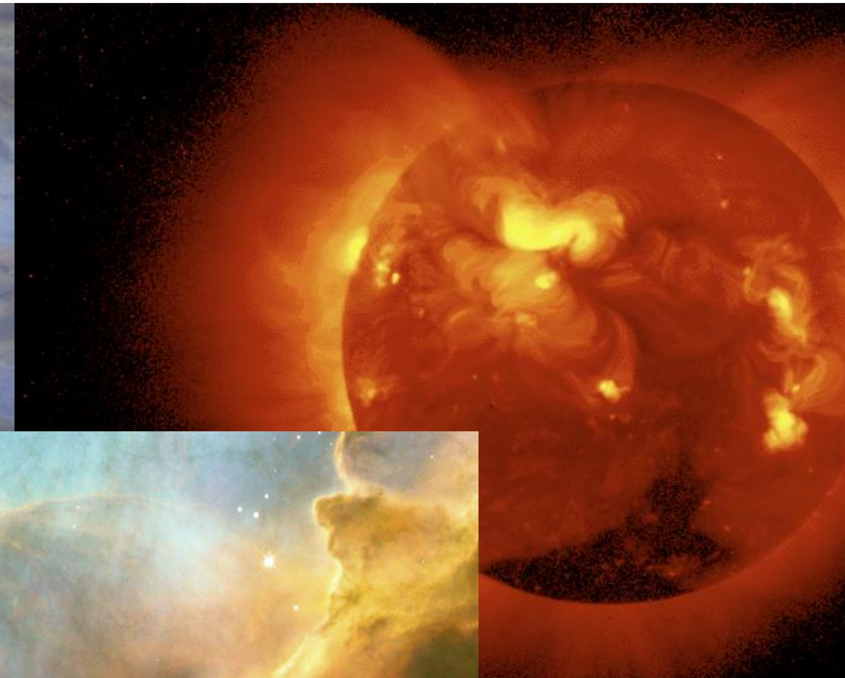


Extreme large-scale rotational flows, wall bounded, driven by buoyancy + amplification and concentration of existing rotation.

A combination of shear-layers, wall-bounded flow, buoyancy (thermal + latent heat + humidity), and wake turbulence (amplifier: condensation releases heat, heat increase buoyancy, more updraft)

Galactic, Planetary, and Stellar





Turbulent Dynamics are fundamental and widespread - not only on Earth

What is Turbulence?

Early View

Leonardo da Vinci 1452 – 1519

Sketch: water flowing from a culvert

The Deluge

Sketch: Turbulent Wakes 1509

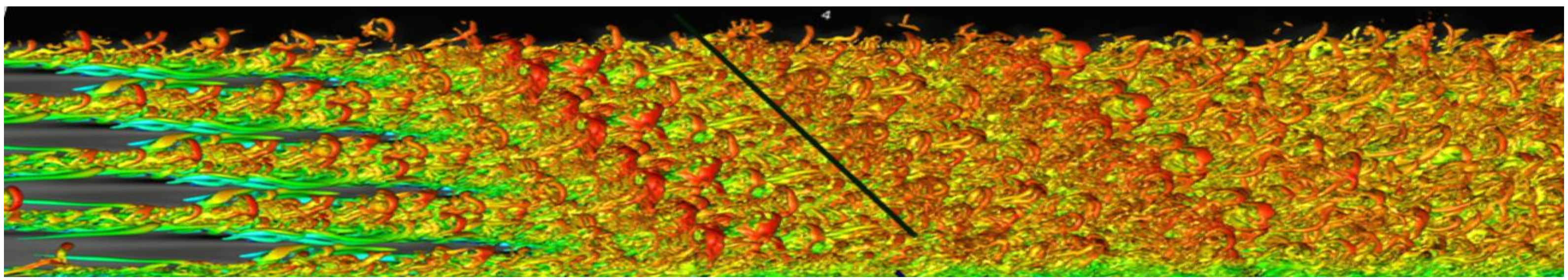
Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the curls; thus the water has eddying motion, one part of which is due to the principal current, the other to random and reverse motion”

Translated by U. Piomelli

Modern View: Mean Flow + Unsteady Vortex Structure

What makes it turbulent?

Laminar flow Smooth Steady	→	Transitional flow Smooth but growing Instabilities	→	Turbulent flow Chaotic Highly Unsteady



L

Flows have a tendency to develop instabilities – controlled by Inertial forces ρU^2
Flows tend to be damped by viscosity – controlled by viscous shear forces $\mu(U/L)$

Balance (Inertial/viscous) is given by Reynolds Number

μ =viscosity
U = velocity
L = length scale (e.g. distance from leading edge)
ν = μ/ρ kinematic viscosity
Pipe flow experiments, O. Reynolds circa 1895

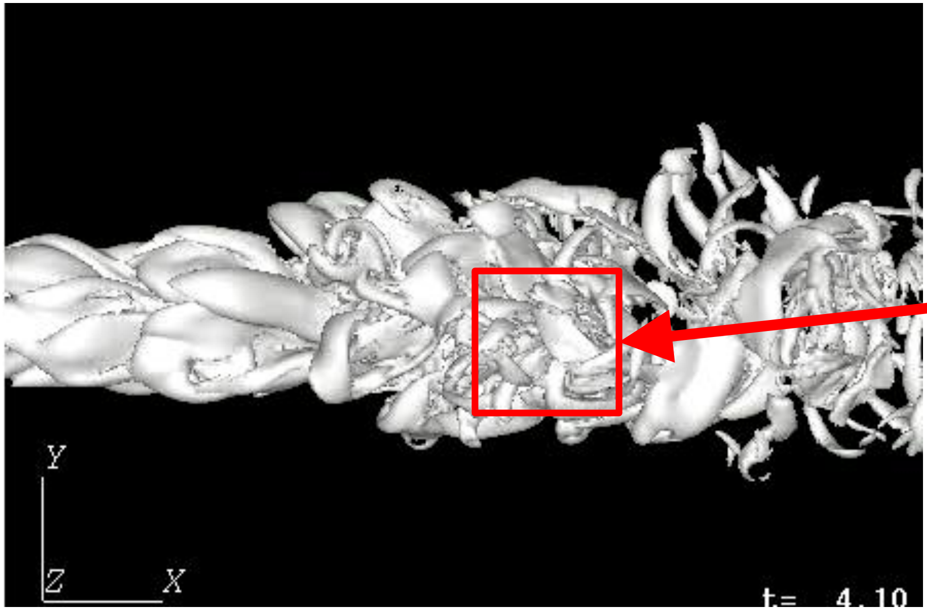
$$Re = \frac{\rho U L}{\mu}$$

$$Re = \frac{UL}{\nu}$$

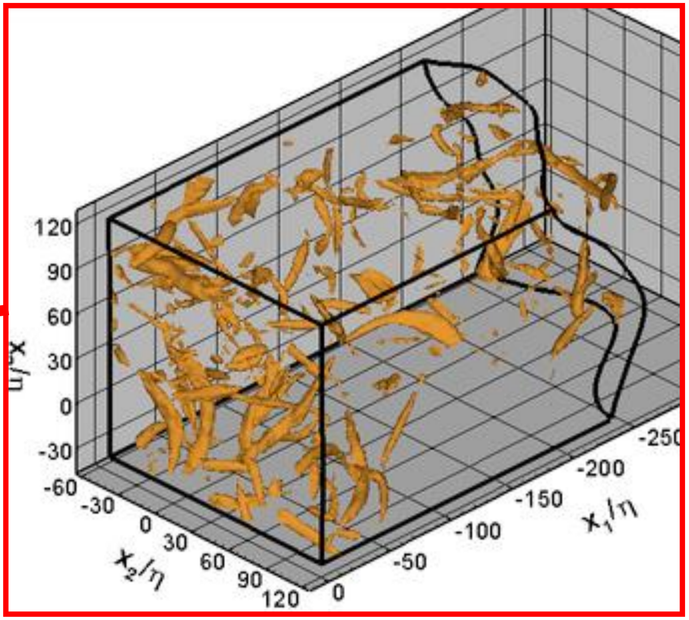
Is there any structure?

"Chaotic" and unsteady with wide range of interacting eddies
However, there is some degree of organisation

"Big whorls have little whorls that feed on their velocity, and little whorls have lesser whorls and so on to viscosity" Idea of cascade.
-L.F. Richardson, 1922



Courtesy: S. Lardeau

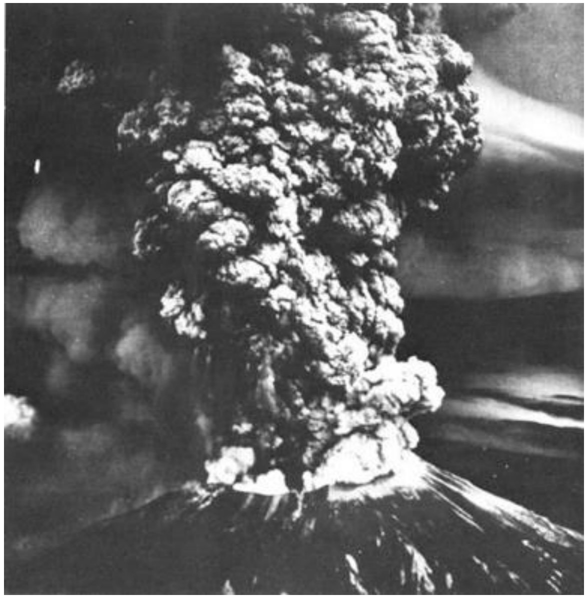


Zoomed in view

Range of Scales

Reynolds Number also indicates the range of scales in a turbulent flow

Higher Re => larger range, greater ratio between largest and smallest eddy size. High Re allows the extension of the small-scale spectrum where most of the dissipation happens, idea of cascade)



Here the scale L is very large (geo-scale) and hence Re >> 1

Most high Re processes are highly non-linear and non-local with multiscale interactions

Turbulence

“Last unsolved problem in classical physics”

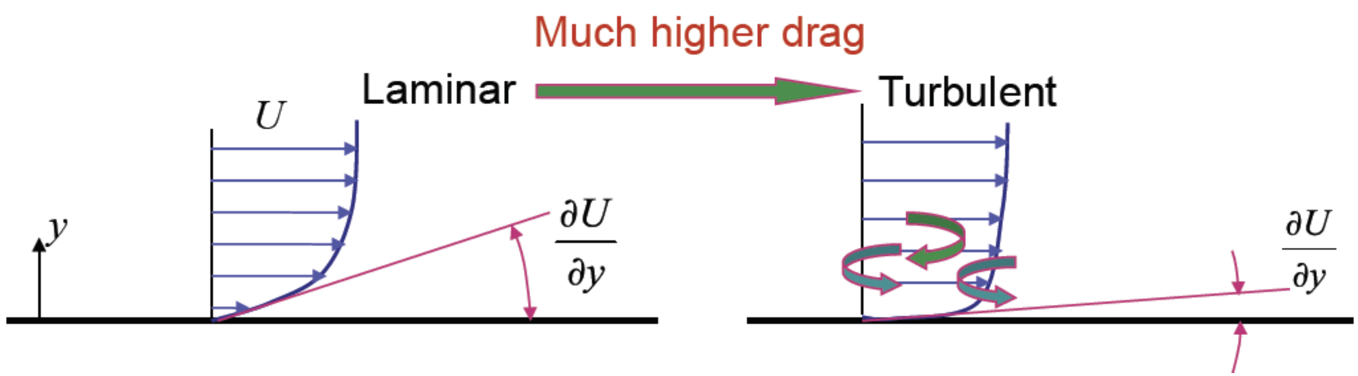
A wide variety of engineering applications:

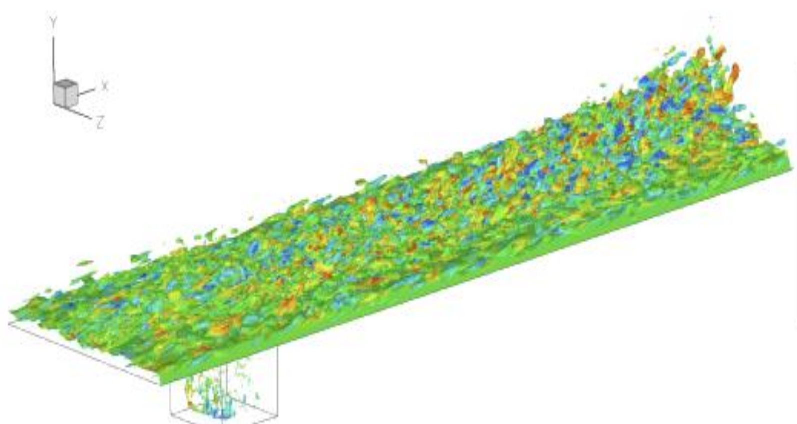
- Drag, energy loss => fuel consumption, range, economy
- Maximum lift, stall => landing, take-off speed, weight
- Aircraft, cars, trucks, trains, ships
- Noise – from aircraft, road vehicle and engine
- Combustion, engine emissions
- Vibrations, buffet, flutter
- Mixing, dispersion
- Erosion
- Heat transfer, heating, cooling

Understanding, Predicting and Controlling Turbulence is of enormous importance

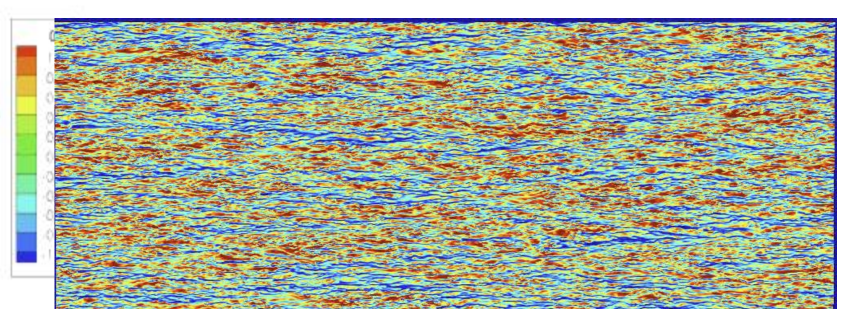
Engineering Applications

Higher skin friction => drag, and energy loss in transport systems
Aircraft 50% Ships 70% Gas Pipelines 90%





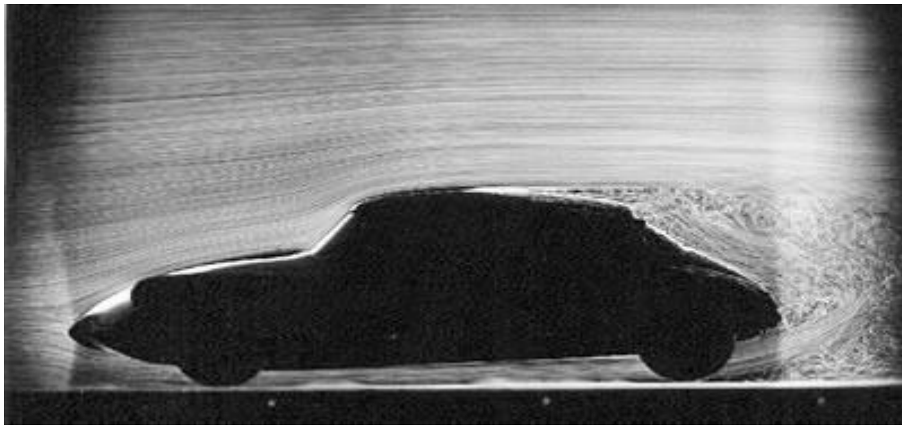
Source: Fishpool & Leschziner

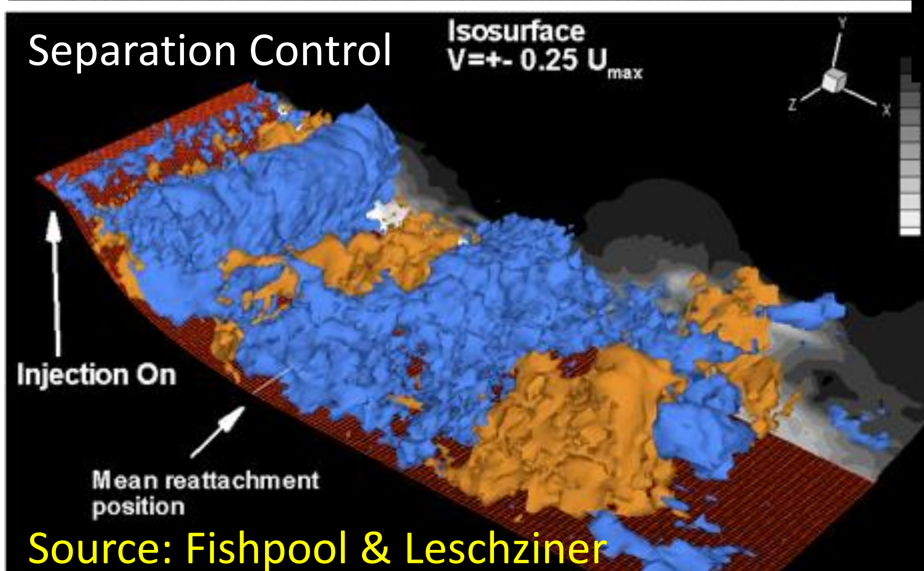


Bes shear stress – streak structures

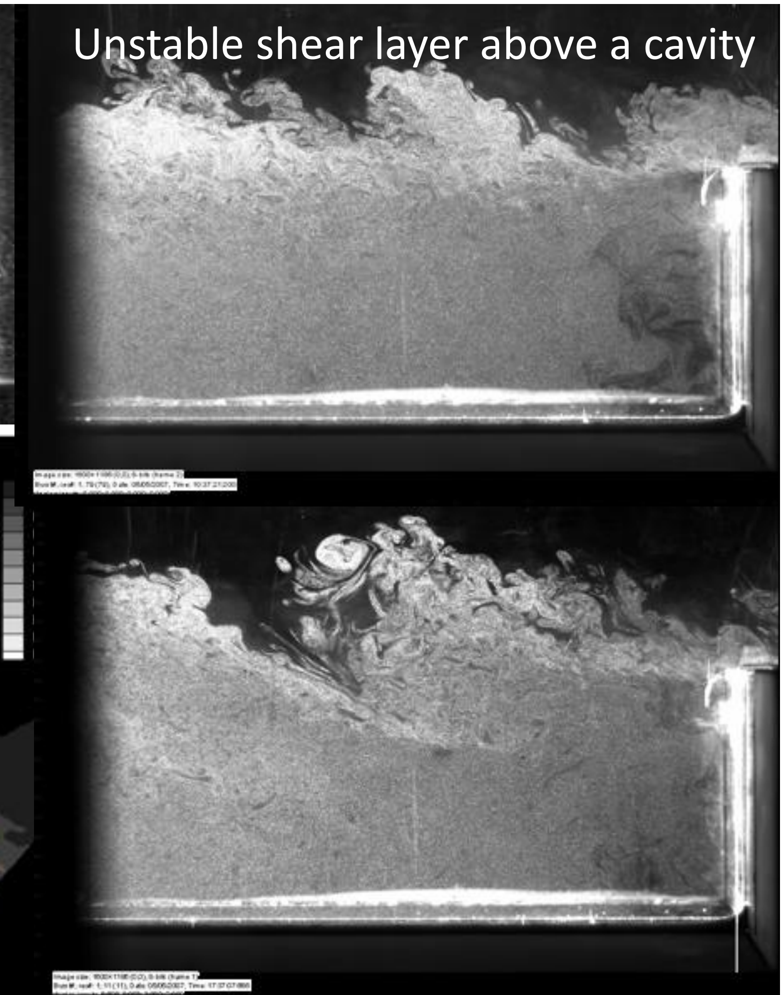
Engineering - Automotive

Separation leads to higher form drag

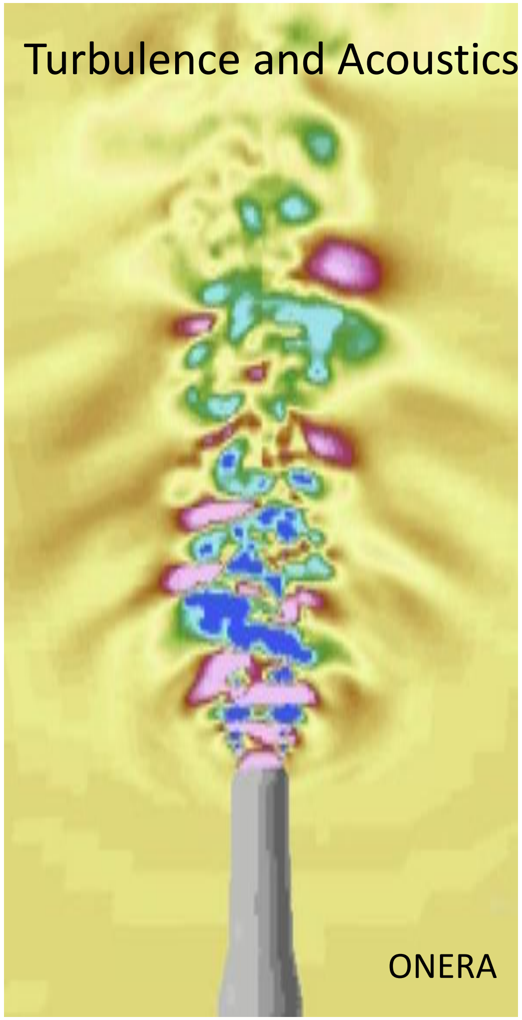


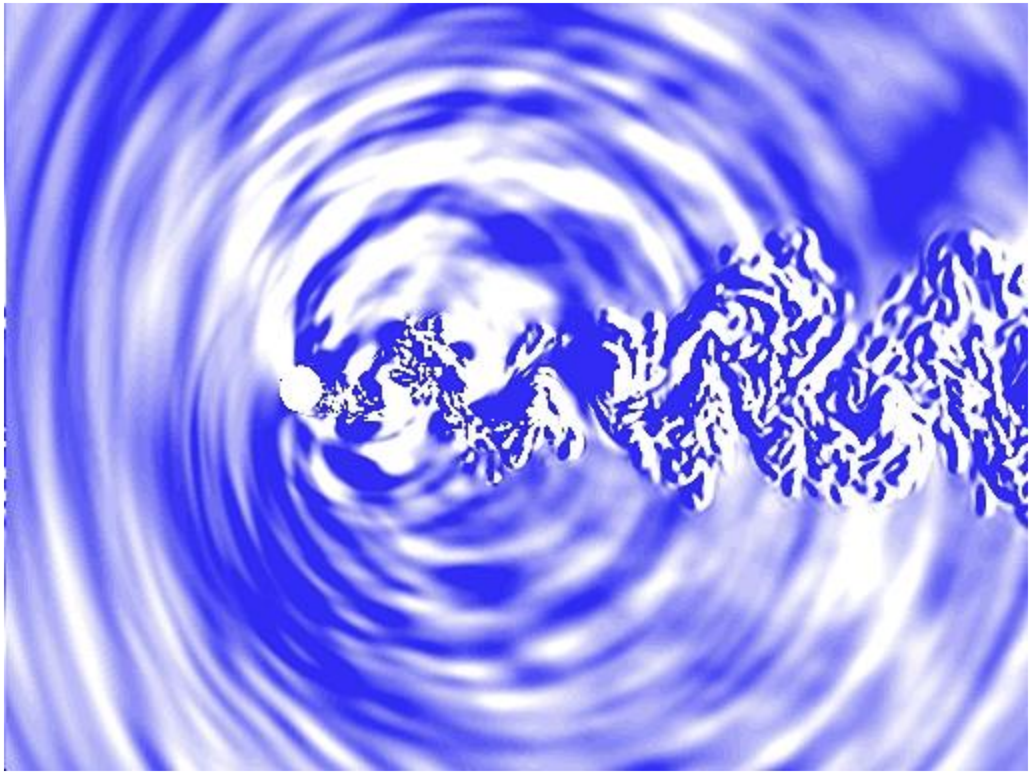


Cavity Drag – aircraft, lorries, etc.



Engineering - Acoustics

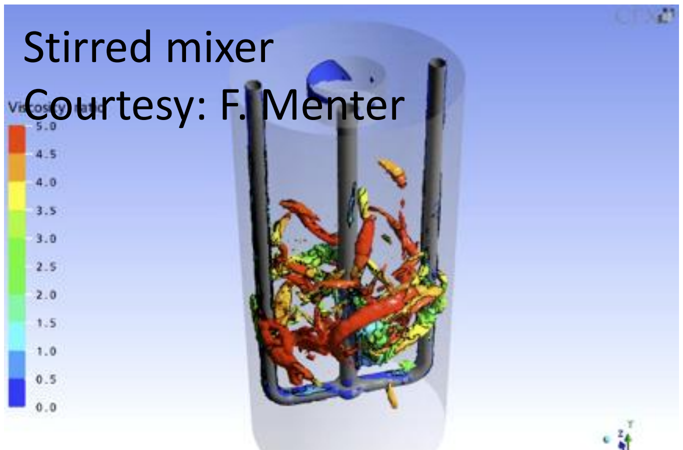




Ali Mani, Meng Wang and Parviz Moin, CTR, Stanford University

Turbulent flow can radiate sound waves: Jet and Wake examples

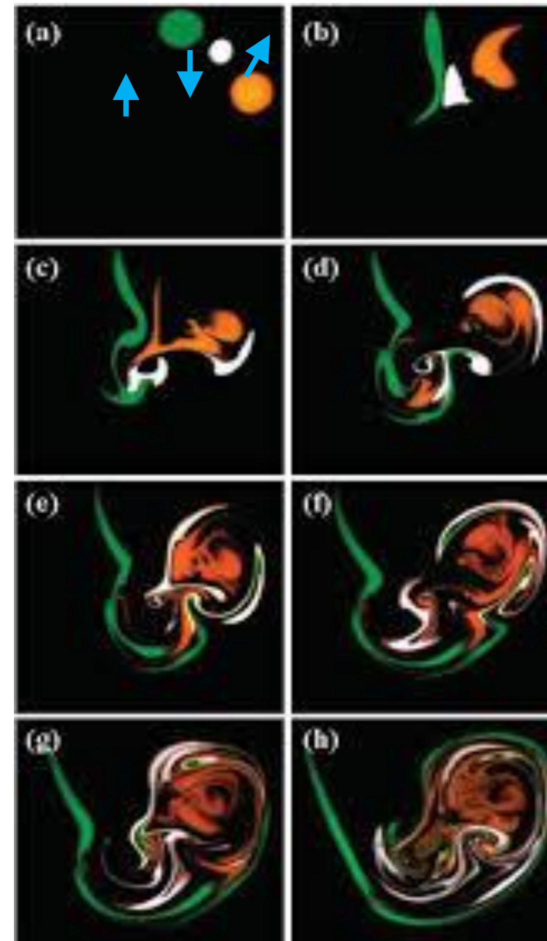
Engineering – Mixing Processes

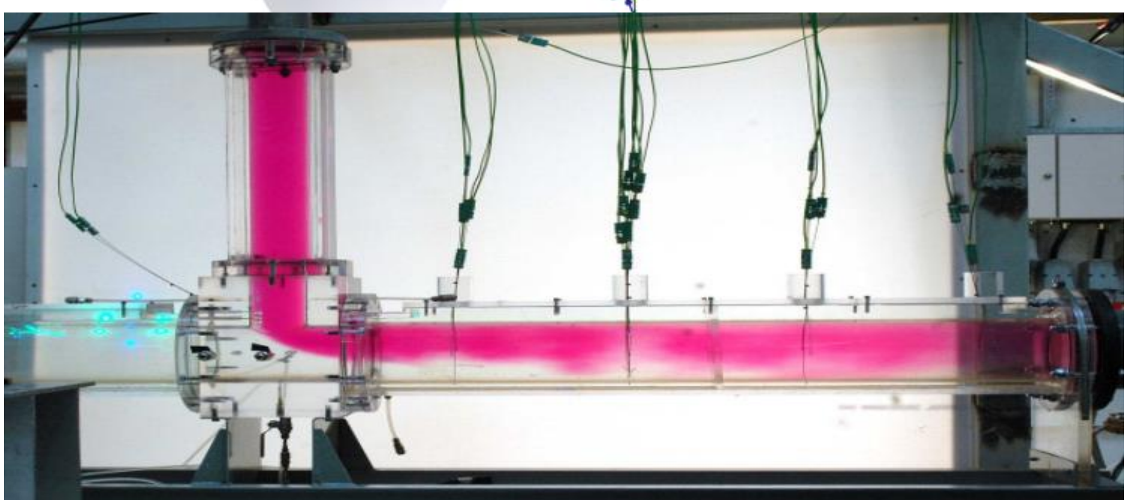


Stirred mixer
Courtesy: F. Menter

Mixing by multi-scale turbulent flow (**continuous stretching** and **shearing** of the tracer volume)

Kewcharoenwong, Rossi & Vassilicos

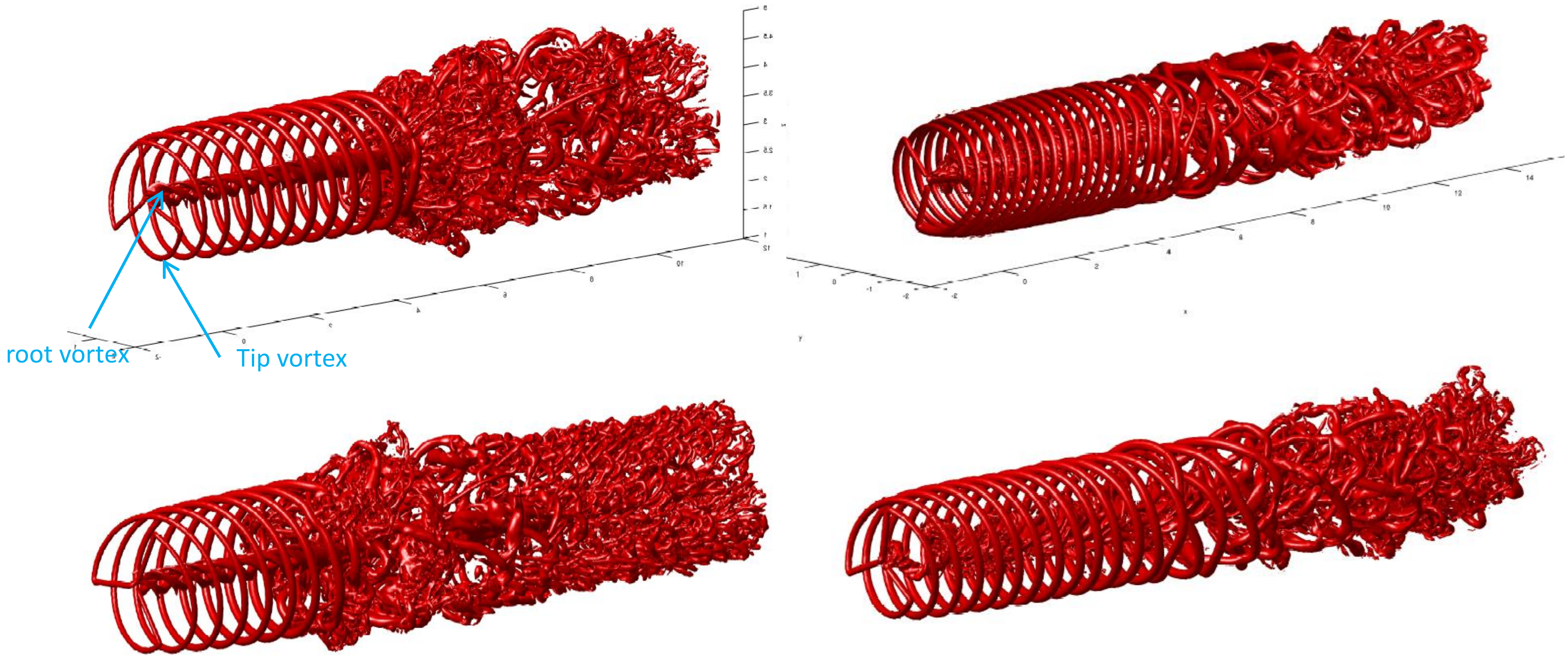




Mixing in a Pipe T-Junction (F. Menter)

Rotor Wakes – Wind Turbine and Rotorcraft Wakes

Turbulent wake instability and turbulent transitions in a rotorwake (various parameters).



Turbulence Rotor Wakes. Solution using embedded Blade-Element Actuator-Line and Navier-Stokes DNS/LES Simulation (T G Thomas).

Turbulence Lectures

In this module we limit ourselves to
Continuum flows of an incompressible, single-phase, Newtonian fluid

Continuum: Model the fluid from a macroscopic view rather than the microscopic viewpoint. Ignore fact that it is actually made up od particles.

We assume that the fluid flow scales are much larger than the mean free path λ of the molecular motion.

Characterised by Knudsen number

$$Kn = \lambda/L$$

Incompressible: Assume that fractional changes in density are small compared to fractional changes in velocity or other quantities, satisfied for small Mach number $M^2 \ll 1$

Density approximately constant along a streamline.

Turbulence Lectures

In this module we limit ourselves to
Continuum flows of an incompressible, single-phase, Newtonian fluid

Two-phase flows are what they seem – mixtures of two phases (steam, oil & water, &c). Many engineering and environmental flows are genuinely two-phase, but the complications are considerable and we avoid them here.

Restrict to mono-phase in this module.

Newtonian fluids are those with *linear* relation between constitutive stress τ_{ij} and rate of strain S_{ij}

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) = 2\mu S_{ij}$$

Viscous stress S = strain rate

Note: We will try to use tensor notation (also known as Einstein summation convention most times)