Turbulence and CFD models: Theory and applications

Roadmap to Lecture 4

1. **Practical turbulence estimates**

Introduction

- In Lecture 3, Kolmogorov scales, Taylor scales, and integral scales were introduced.
- We then explored the concepts of energy spectrum, energy cascade, integral length scale, and grid length scale.
- We also studied the basic concepts of turbulence near the wall, we introduced the Law of the Wall, and the non-dimensional quantity y^+.
- Finally, we took a glimpse to a turbulence model.
- At this point, the question is,
  - How can we use this information?
  - How can we get an initial estimate of the new variables related to the turbulence model?
  - How can we estimate the meshing requirements?
- Hereafter, we will give some standard practices on how to get turbulence estimates.

Introduction

- Using everything we have learned so far, we can get global estimates for the following variables:
    - Eddy velocity, size, and time scales (integral, Taylor, and Kolmogorov).
    - Number of grid points needed.
    - Energy dissipation rate ϵ.
    - Turbulent kinetic energy k.
    - Turbulent kinematic viscosity μ_t.
    - Turbulent intensity I_t.
    - y^+.
- Remember, we will compute initial estimates for global quantities.
- If you want to get the local values, you will need to run a simulation.
- I cannot stress this enough; we will compute rough estimates which are fine for initial conditions or generating an initial mesh.

Practical turbulence estimates

Introduction

- Let us first compute the integral eddy length scale, turbulence intensity, turbulent kinetic energy, and turbulent dissipation
- We will use the **LIKE** acronym [1] to describe the workflow that we will use to compute these practical estimates.

• **L**	=	l	=	integral eddy length scale
• **I**	=	I_t	=	turbulence intensity
• **K**	=	k	=	turbulent kinetic energy
• **E**	=	ϵ	=	turbulent dissipation

- We already know many relations from Lecture 3.
- We will introduce a few new equations.
- Many of these relationships can be derived from dimensional analysis.
- Remember to always check the dimensional groups.

[1] S. Rodriguez. “Applied Computational Fluid Dynamics and Turbulence modeling”. Springer, 2019.

A reminder about the units

Derived quantity	Symbol	Dimensional units	SI units
Velocity	u	LT^{-1}	m/s
Density	ρ	ML^{-3}	kg/m^3
Kinematic viscosity	ν	L^2T^{-1}	m^2/s
Dynamic viscosity	μ	$ML^{-1}T^{-1}$	kg/m-s
Energy dissipation rate per unit mass	ϵ	L^2T^{-3}	m^2/s^3
Turbulent kinetic energy per unit mass	k	L^2T^{-2}	m^2/s^2
Length scales	l	L	m
Wavelength	κ	L^{-1}	1/m
Intensity	I_t	-	-

Practical turbulence estimates

Integral eddy length scale – LIKE

- Usually, the integral scales are represented by a characteristic dimension of the domain,

$$l \sim x_{char}$$

- That is, the system characteristic length places a limit on the maximum integral eddy length.
- In practice, this limit is not reached nor there is a typical value.
- Therefore, conservative approximations are often used based on a percentage of the system characteristic length.
- For example,
  - If you are simulating the flow about a cylinder, you can say that the largest eddies are about 70% of the cylinder diameter.
  - If you are simulating the flow in a pipe, you can say that the largest eddies are about the diameter of the pipe.
  - If you are simulating the flow about an airfoil (with no large flow separation), you can say that the largest eddies are about the airfoil thickness.

Practical turbulence estimates

Integral eddy length scale – LIKE

- You will find often the following relationships in the literature.
  - For internal flows (pipes and ducts), where D is the diameter or height,

$$l \approx 0.07D$$

  - For boundary layers over surfaces, where δ is the turbulent boundary layer thickness,

$$l \approx 0.4\delta$$

where the boundary layer thickness can be approximated using the following correlation (among many available in the literature),

$$\delta \approx \frac{0.37x}{Re_x^{1/5}}$$

Integral eddy length scale – LIKE

- You will find often the following relationships in the literature.
  - For grid generated turbulence in wind tunnels, where *S* is the grid spacing,

$$l \approx 0.2S$$

  - The following is a personal estimate that I often use,

$$l \approx 0.7h_b$$

- Where h_b is the blockage height in the direction of the incoming flow.
- For example:
  - Airfoil thickness, if it is aligned with the flow or at a low AOA.
  - If the airfoil is at a high AOA, the blockage height.
  - Frontal area of a body (cylinder, truck, and so on).
- This relationship can be use for internal and external flows

Integral eddy length scale – LIKE

- If you have estimates for k and ϵ, you can compute the integral length scales as follows.
  - Taylor suggests [1] that the integral length scales can be approximated as follows,

$$l \approx \frac{k^{3/2}}{\epsilon}$$

Use this estimate if you are interested in the largest integral length scale

  - This estimate can be improved by using experimental data, as explained by Wilcox [2],

$$l = C_\mu \frac{k^{3/2}}{\epsilon} \quad \text{where} \quad C_\mu = 0.09$$

Use this estimate if you are interested in the average integral length scale

[1] G. I. Taylor. Statistical theory of turbulence. Proceedings of the Royal Society of London. 1935.
[2] D. Wilcox. Turbulence Modeling for CFD. DCW Industries Inc., 2010.

Turbulence intensity – LIKE

- The turbulence intensity (also called turbulence level) is often abbreviated as follows,

$$I \qquad I_t \qquad T_u \qquad T' \qquad T_L$$

- The turbulence intensity can be computed as follows,

$$I = \frac{u'}{\overline{u}}$$

Intensity of velocity fluctuations (u')

Mean velocity – Freestream velocity ($\overline{u}$)

- The intensity of the velocity fluctuations (turbulence strength) is defined by the root mean square (RMS) of the velocity fluctuations,

$$u' = u_{RMS} = \sqrt{\frac{1}{3}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)}$$

It gives a measure of the dispersion of the velocity fluctuations squared (normal Reynolds stresses). It is nothing else that the standard deviation of the fluctuations.

Do not confuse this value (**intensity of velocity fluctuations**) with this value (**x component of the velocity fluctuation**)

Turbulence intensity – LIKE

- The Reynolds stress components $\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$, can also be regarded as the kinetic energy per unit mass of the fluctuating velocity in the three spatial directions.
- If we sum the normal Reynolds stresses and multiply by 0.5, we obtain the turbulent kinetic energy,

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) = \frac{1}{2}\overline{u'_i u'_i}$$

- The normal Reynolds stresses can be normalized relative to the mean flow velocity, as follows,

$$\widehat{u} \equiv \frac{\sqrt{\overline{u'^2}}}{\overline{u}} \qquad \widehat{v} \equiv \frac{\sqrt{\overline{v'^2}}}{\overline{u}} \qquad \widehat{w} \equiv \frac{\sqrt{\overline{w'^2}}}{\overline{u}}$$

These three quantities are known as relative intensities.

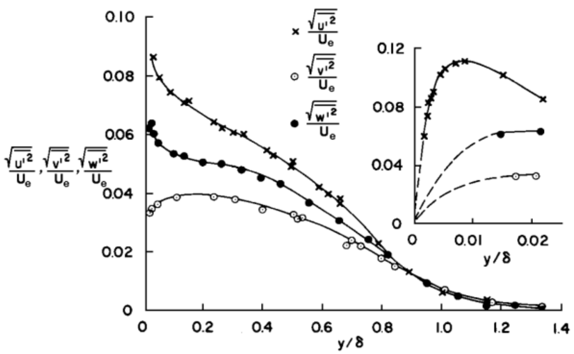
Practical turbulence estimates

Turbulence intensity – LIKE

- For anisotropic turbulence (*i.e.*, the normal-stress components are unequal), a rough but useful estimate to the normal components is the following,

$$\overline{u'^2} : \overline{v'^2} : \overline{w'^2} \approx 4 : 2 : 3$$

Based on flat-plate boundary layer



Turbulence intensities for a flat-plate boundary layer of thickness δ [1].

- For the case of isotropic turbulence or $\overline{u'^2} = \overline{v'^2} = \overline{w'^2}$,

$$I = \sqrt{\frac{\frac{2}{3}k}{\bar{u}^2}} = \frac{\sqrt{\frac{2}{3}k}}{\bar{u}}$$

[1] P. Klebanoff. “Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient”. NACA TN 1247, 1955.

Turbulence intensity – LIKE

- To use the previous relations you need to have some form of measurements or previous experience to base the estimate on.
- The turbulence intensity can also be estimated using empirical correlations.
- For instance, if you are working with pipes, there are many correlations that are expressed in the form of a power law,

$$I = C_1 Re_h^{-C_2}$$

Hydraulic Reynolds number

- One widely used correlation is the following one,

$$I = 0.16 Re_h^{-1/8}$$

- Remember, there are many forms of these correlations (for smooth and rough pipes).

Practical turbulence estimates

Turbulence intensity – LIKE

- If you are working with external aerodynamics, it might be a little bit more difficult to get rule of thumb estimates.
- However, the following estimates are acceptable,

	Low	Medium	High
I_t	1.0 %	5.0 %	10.0 %

- **Low turbulence intensity:** external flow around cars, ships, submarines, and aircrafts. Very high-quality wind-tunnels can also reach low turbulence levels, typically below 1.0%.
- **Medium turbulence intensity:** flows in not-so-complex devices like large pipes, fans, ventilation flows, wind tunnels, low speed flows, and fully-developed internal flows. Typical values are between 2.0% and 7.0%.
- **High turbulence intensity:** high-speed flow inside complex geometries like heat-exchangers and rotating machinery (turbines and compressors). Typical values are between 10.0% and 20.0%.

Practical turbulence estimates

Turbulent kinetic energy – LIKE

- The turbulent kinetic energy k is also known as TKE.
- If you have some estimates of the normal Reynolds stresses, the TKE (per unit mass) can be computed as follows,

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

- Otherwise, you can use a rule of thumb turbulence intensity estimate and compute TKE as follows,

$$k = \frac{3}{2}\left(\overline{u}I\right)^2$$

where $\overline{u}$ is the freestream velocity

- Instead of using $\overline{u}$, you can also use a value slightly higher that we will call turbulent freestream value u_{tur} ,

Arbitrary constant to correct velocity fluctuations

$$u_{tur} \approx C\overline{u} = \frac{11}{10}\overline{u}$$

Practical turbulence estimates

Energy dissipation rate – LIKE

- Once TKE is known, together with a crude estimate of the integral eddy length scale, the energy dissipation rate ϵ (per unit mass) can be computed as follows,

$$\epsilon = C_\mu \frac{k^{3/2}}{l} \qquad \text{where} \qquad C_\mu = 0.09$$

- You can compute the specific dissipation rate once you know ϵ and l, as follows,

$$\omega = \frac{\epsilon}{\beta^* k} \qquad \text{where} \qquad \beta^* = \frac{9}{100}$$

- You can compute the integral eddy length scale from specific dissipation rate as follows,

$$l = \frac{k^{1/2}}{\omega}$$

Turbulent viscosity

- So far, we computed the integral eddy length scale, turbulence intensity, turbulent kinetic energy and energy dissipation rate.
- In the previous lecture, we saw that in turbulence modeling there is an extra ingredient, turbulent viscosity μ_t.
- We can also get an estimate for this quantity. How do we estimate it depends on the turbulent model.
- For example, the $k-\omega$ model computes the turbulent viscosity as follows,

$$\mu_t = \frac{\rho k}{\omega}$$

Where you can compute ω from ϵ as follows,

$$\omega = \frac{\epsilon}{\beta^* k} \qquad \beta^* = \frac{9}{100}$$

- As usual, check the dimensional groups.
- Remember, the turbulent viscosity is not a physical quantity.
- Also, the turbulent viscosity is larger than the laminar viscosity (molecular viscosity).

Turbulent viscosity

- We can also use a rule of thumb to get a fast estimate of the turbulent viscosity.
- Using the turbulence intensity I_t, we can get an estimate for the viscosity ratio μ_t/μ as follows,

	Low	Medium	High
I_t	1.0 %	5.0 %	10.0 %
μ_t/μ	1-2	10	100

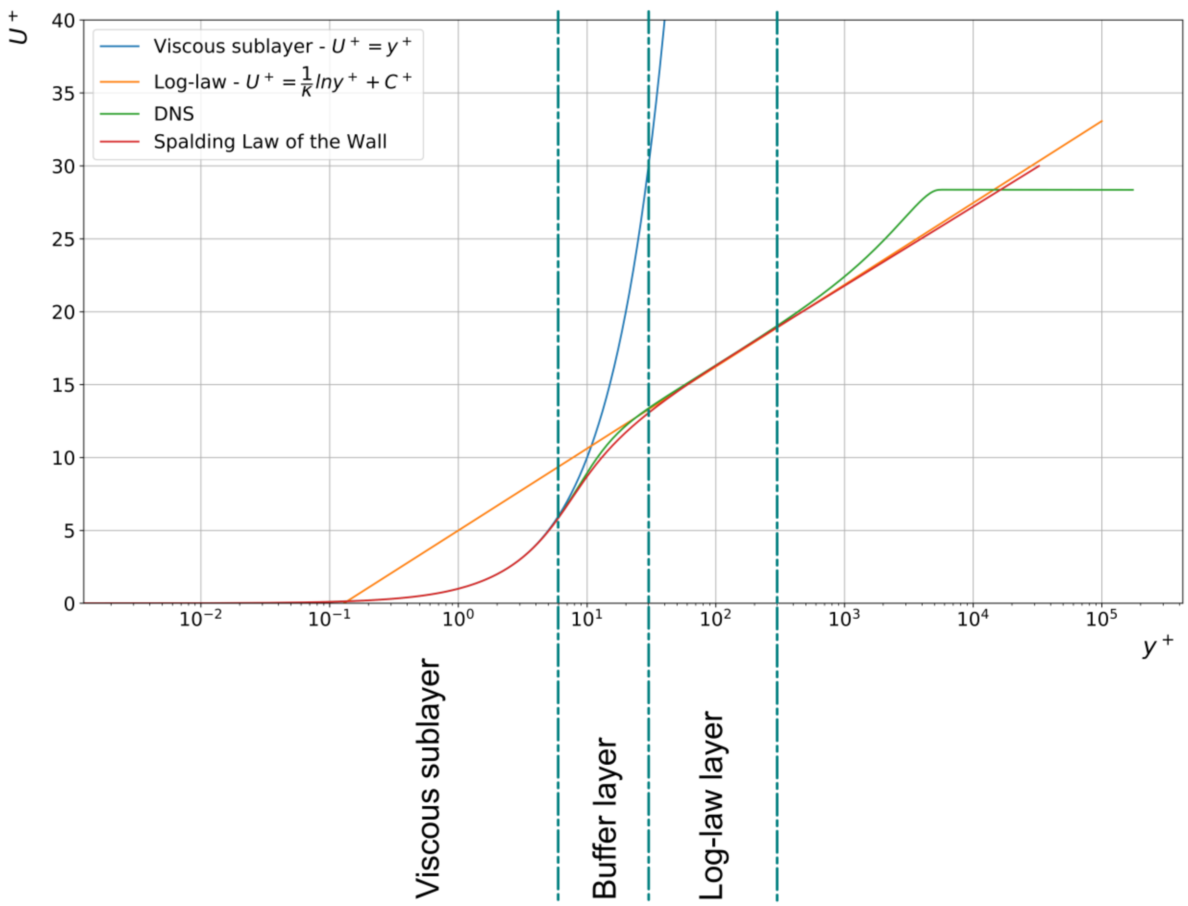
Low turbulence intensity (1%): external flow around cars, ships, submarines, and aircrafts. Very high-quality wind-tunnels can also reach low turbulence levels, typically below 1.0%.

Medium turbulence intensity (5%): flows in not-so-complex devices like large pipes, fans, ventilation flows, wind tunnels, low speed flows, and fully-developed internal flows. Typical values are between 2.0% and 7.0%.

High turbulence intensity (10%): high-speed flow inside complex geometries like heat-exchangers and rotating machinery (turbines and compressors). Typical values are between 10.0% and 20.0%.

- We usually use these estimates when dealing with external aerodynamics.

Estimation of y^+



$$y^+ = \frac{\rho \times U_\tau \times y}{\mu} = \frac{U_\tau \times y}{\nu}$$

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

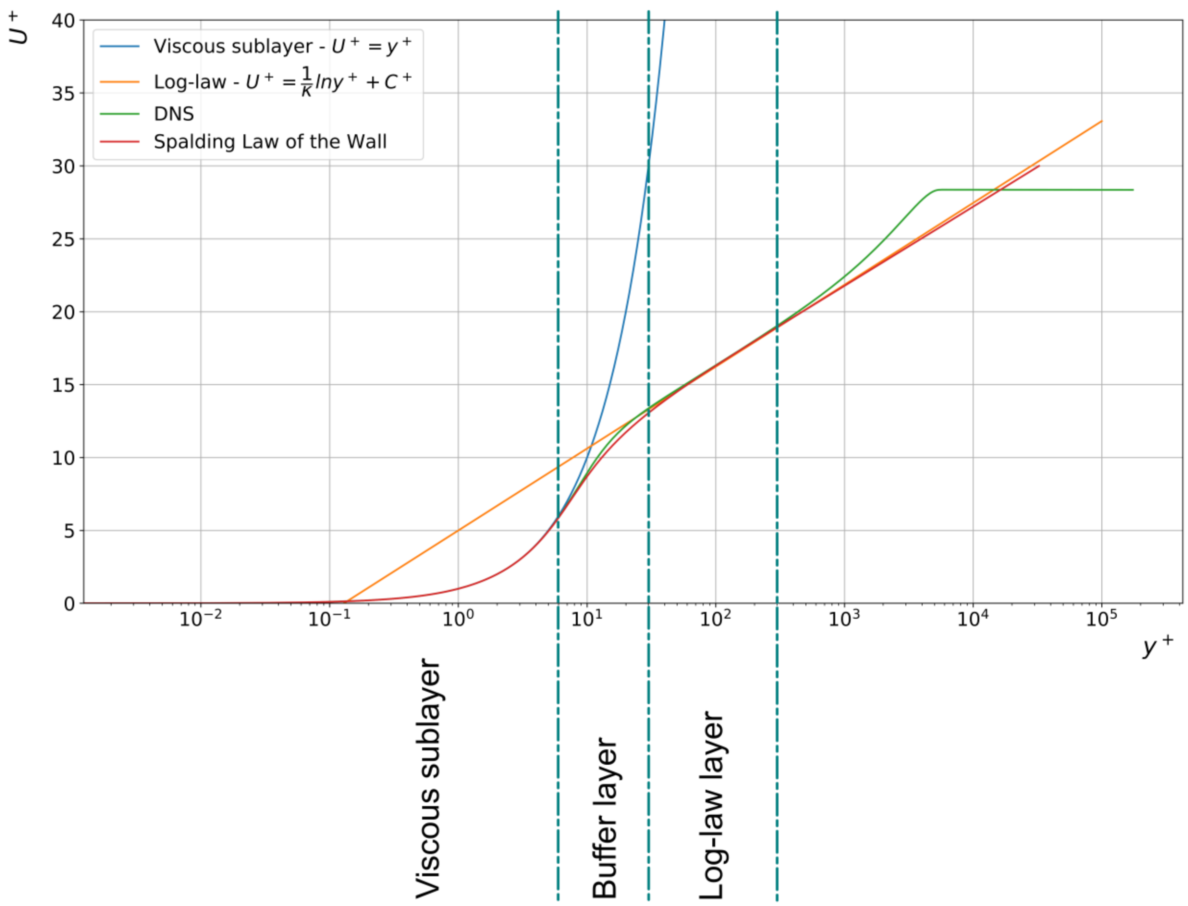
$$u^+ = \frac{U}{U_\tau}$$

Where y is the distance normal to the wall, U_τ is the shear velocity, and u^+ relates the mean velocity to the shear velocity

- y^+ or wall distance units is a very important concept when dealing with turbulence modeling.
- Remember this definition as we are going to use it a lot.

Practical turbulence estimates

Estimation of y^+



$$30 < y^+ < 300$$

$$u^+ = \frac{1}{\kappa} \ln y^+ + C^+$$

$$\kappa \approx 0.41 \quad C^+ \approx 5.0$$

$$y^+ < 6$$

$$u^+ = y^+$$

$$6 < y^+ < 30$$

$$u^+ \neq y^+$$

$$u^+ \neq \frac{1}{\kappa} \ln y^+ + C^+$$

Note: the range of y^+ values might change from reference to reference but roughly speaking they are all close to these values.

Estimation of y^+

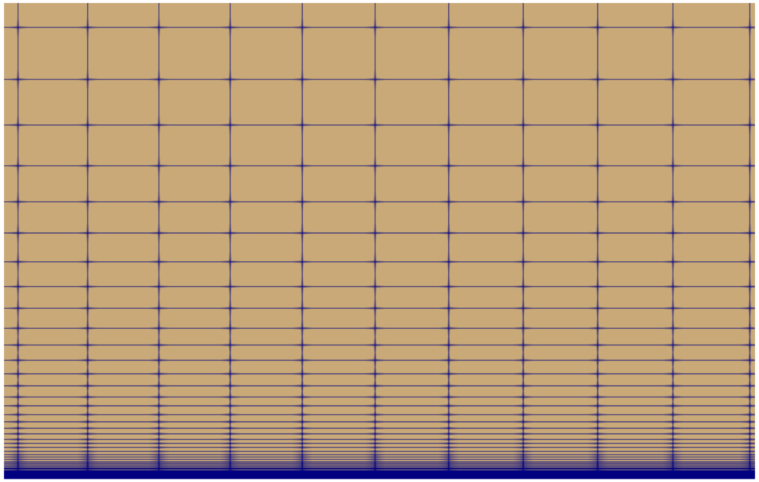
- y^+ is very important quantity in turbulence modeling.
- We can use y^+ to estimate the mesh resolution near the wall before running the simulation.
    - We do not know a-priori the wall shear stresses at the walls; therefore, we need to use correlations to get a rough estimate and generate the initial mesh.
    - The initial mesh is generated according to the chosen near the wall treatment (wall resolving, wall functions, or y^+ insensitive).
    - Then, we run a precursor simulation to get a better estimate y^+ and determine where we are in the boundary layer.
    - It is an iterative process and it can be very time consuming, as it might require remeshing and rerunning the simulation to satisfy the near the wall treatment.

Estimation of y^+

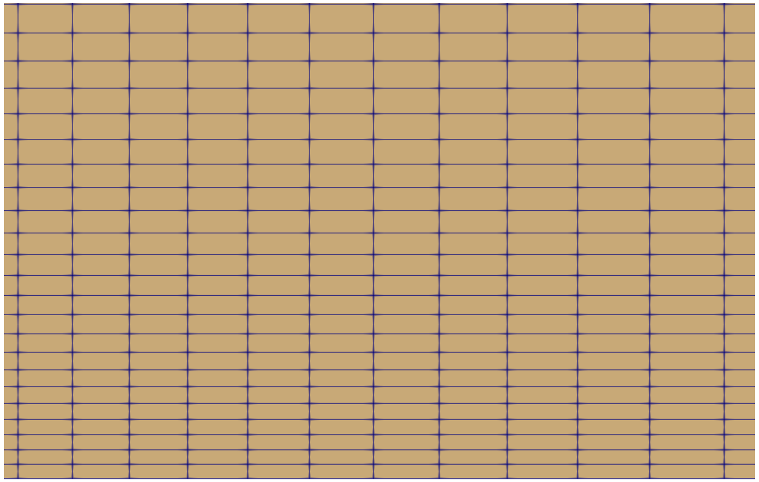
- y^+ always needs to be monitored during the simulation.
    - Have in mind that it is quite difficult (if not impossible) to get a uniform y^+ value at the walls.
    - We usually monitor the average y^+ value. If this value covers approximately 80% of the wall, we can take the mesh as a good one.
    - Otherwise, we need to refine or coarse the mesh to ger a more uniform distribution of y^+.
    - It is also important to monitor the maximum values of y^+. It is not a got practice to have values larger than 1000.
    - Values of y^+ up to 300 are fine.
    - Values of y^+ larger than 300 and up to a 1000 are acceptable if they do not cover a large surface area (no more than 10% of the total wall area), or if they are not located in critical zones.
    - It is also important to monitor the minimum y^+, as some models might have problems with low y^+ values.
    - Use common sense when accessing y^+ value.

Estimation of y^+

- At meshing time, to estimate the normal distance from the wall to the first cell center (y), we use the well known y^+ definition.
- Where we set a target y^+ value and then we solve for the quantity y.
  - If you choose a low y^+ (less than 10), you will have a mesh that is clustered towards the wall (small value of y).
  - If you choose a large y^+ value (let us say 100), you will have a coarse mesh towards the walls (large value of y).



Fine mesh towards the walls



Corse mesh towards the walls

Note: depending on the implementation you will need to use the cell center or cell vertex.

Estimation of y⁺

- At meshing time, to estimate the normal distance from the wall to the first cell center, we use the well known y^+ definition,

$$y^+ = \frac{\rho \times U_\tau \times y}{\mu} = \frac{U_\tau \times y}{\nu}$$

- The problem is that at meshing time we do not know the value of the shear velocity,

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

- So, how do we get an initial estimate of this quantity?

Estimation of y+

- At meshing time, to estimate the normal distance from the wall to the first cell center, you can proceed as follows,

1. $$Re = \frac{\rho \times U \times L}{\mu}$$

Compute the Reynolds number using the characteristic length of the problem.

2. $$C_f = 0.058 \times Re^{-0.2}$$

Compute the friction coefficient using any of the correlations available in the literature. There are many correlations available that range from pipes to flat plates, for smooth and rough surfaces.

This correlation corresponds to a smooth flat plate case, ideal for external aerodynamics.

3. $$\tau_w = \frac{1}{2} \times C_f \times \rho \times U_{\infty}^2$$

Compute the wall shear stresses using the friction coefficient computed in the previous step.

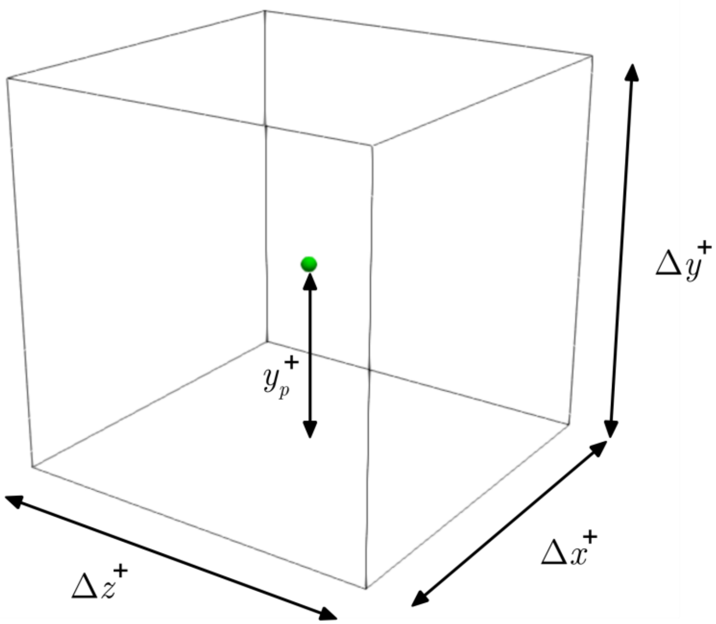
4. $$U_{\tau} = \sqrt{\frac{\tau_w}{\rho}}$$

Compute the shear velocity using the wall shear stresses computed in the previous step.

5. $$y = \frac{\mu \times y^+}{\rho \times U_{\tau}}$$

Set a target y^+ value and solve for y using the flow properties and previous estimates.

Wall distance units x+ – y+ – z+



- Similar to y^+, the wall distance units can be computed in the stream-wise (Δx^+) and span-wise (Δz^+) directions.
- The wall distance units in the stream-wise and span-wise directions can be computed as follows:

$$\Delta x^+ = \frac{U_\tau \Delta x}{\nu} \qquad \Delta z^+ = \frac{U_\tau \Delta z}{\nu}$$

- And recall that y^+ is computed at the cell center, therefore:

$$\Delta y^+ = 2 \times y^+$$

$$(\Delta x^+, \Delta y^+, \Delta z^+) = \left(\frac{x}{l_\tau}, \frac{y}{l_\tau}, \frac{z}{l_\tau} \right)$$

where

$$l_\tau = \frac{\nu}{U_\tau}$$

Viscous length

Practical turbulence estimates

Wall distance units – A few mesh resolution guidelines and rough estimates

- The mesh is everything in CFD, and when it comes to turbulence modeling it is extremely important to have meshes with good quality and acceptable resolution.
- Some general guidelines for meshes to be used with RANS/DES/LES:
    - Resolve well the curvature.
    - Allow a smooth transition between cells of different sizes (at least 3 cells).
    - Identify the integral scales and try to cluster at least 5 cells in the domain regions where you expect to find the integral scales.
- Some guidelines specific to RANS meshes:
    - When it comes to RANS, the most important metric for mesh resolution is the y^+ value.
    - Choose your wall treatment and mesh your domain according to this requirement.
    - If you are doing 3D simulations, there are no strict requirements when it comes to the span-wise and stream-wise directions.
    - But as a rule of thumb rule you can use Δx^+ and Δz^+ values as high as 300 times the value of Δy^+ and less than a 1000 wall distance units.

Practical turbulence estimates

Wall distance units – A few mesh resolution guidelines and rough estimates

- Some guidelines specific to DES meshes:
  - The mesh requirements are very similar to those of RANS meshes.
  - It is extremely important to resolve well the integral length scales.
- Some guidelines specific to LES meshes:
  - When it comes to LES meshes, it is recommended to use wall functions. Otherwise the meshing requirements are similar to those of DNS.
  - Recommended wall distance units values are,

$$\Delta x^+ < 50,\ \Delta z^+ < 50 \quad \text{for} \quad y^+ < 6$$

Wall resolving

$$\Delta x^+ < 4\Delta y^+,\ \Delta z^+ < 4\Delta y^+ \quad \text{for} \quad 30 \leq y^+ \leq 300$$

Wall modeling

- If you are doing DNS simulations, the requirements for wall distance units in all directions are in the order of 1.
- You might b able to go as high as 10 for Δx^+ and Δz^+.

Practical turbulence estimates

Summary of turbulence length scales

- The Kolmogorov scales are summarized as follows,

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \qquad \tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2} \qquad \upsilon_\eta = (\nu\epsilon)^{1/4}$$

Length scale | Time scale | Velocity scale

- The Taylor microscales are summarized as follows,

$$\lambda = \left(\frac{10\nu k}{\epsilon}\right)^{1/2} \qquad \tau_\lambda = \left(\frac{15\nu}{\epsilon}\right)^{1/2} \qquad u_\lambda = \frac{\lambda}{\tau_\lambda}$$

Length scale | Time scale | Velocity scale

Summary of turbulence length scales

- Taylor suggests [1] that the integral length scales can be approximated as follows,

$$l \approx \frac{k^{3/2}}{\epsilon}$$

- This estimate can be improved by using experimental data [2],

$$l = C_\mu \frac{k^{3/2}}{\epsilon} \qquad \text{where} \qquad C_\mu = 0.09$$

- You can express the previous relation in function of ω as follows,

$$l = \frac{k^{1/2}}{\omega} \qquad \text{where} \qquad \omega = \frac{\epsilon}{\beta^* k} \qquad \text{and} \qquad \beta^* = \frac{9}{100}$$

[1] G. I. Taylor. Statistical theory of turbulence. Proceedings of the Royal Society of London. 1935.
[2] D. Wilcox. Turbulence Modeling for CFD. DCW Industries Inc., 2010.

Summary of turbulence length scales

- The eddies turnover time is the ratio between the integral length scales and the velocity $k^{1/2}$ (the measure of the velocity fluctuations around the mean), and it can be computed as follows,

$$\tau_{turnover} \sim \frac{l}{k^{1/2}} \qquad \tau_{turnover} = \frac{C_\mu k}{\epsilon}$$

- The eddy turnover time is a measure of the time it takes an eddy to interact with its surroundings.
- The integral eddy velocity is the ratio of its integral length scale and its turnover time,

$$u_l = \frac{l}{\tau_{turnover}} = k^{1/2}$$

- If you assume isotropic turbulence then, $u_l = \left(\frac{2k}{3}\right)^{1/2}$

Summary of turbulence length scales

- The different length scales can be related as follows,

$$\frac{l_0}{\eta} \sim Re_T^{3/4}$$

$$\frac{\lambda}{l_0} = \sqrt{10} Re_T^{-1/2}$$

$$\frac{\lambda}{\eta} = \sqrt{10} Re_T^{1/4}$$

$$\lambda = \sqrt{10} \eta^{2/3} l_0^{1/3}$$

- Support equations:

$$Re_T = \frac{k^{1/2} l_0}{\nu} = \frac{k^2}{\epsilon \nu}$$

$$l_0 = \frac{k^{3/2}}{\epsilon}$$

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

$$\lambda = \left(\frac{10 \nu k}{\epsilon}\right)^{1/2}$$

Summary of Reynolds numbers

- The different Reynolds numbers, based on different length scales, can be summarized as follows,

$Re = \frac{UL}{\nu}$	$Re_\lambda = \frac{u'\lambda}{\nu}$	$Re_\eta = \frac{\eta u_\eta}{\nu} = 1$
Flow Reynolds number	Taylor Reynolds number	Kolmogorov Reynolds number

- The turbulent Reynolds number is related to the integral scales. It is a few order of magnitude lower that the flow Reynolds number (on the order of 100 to 10000).

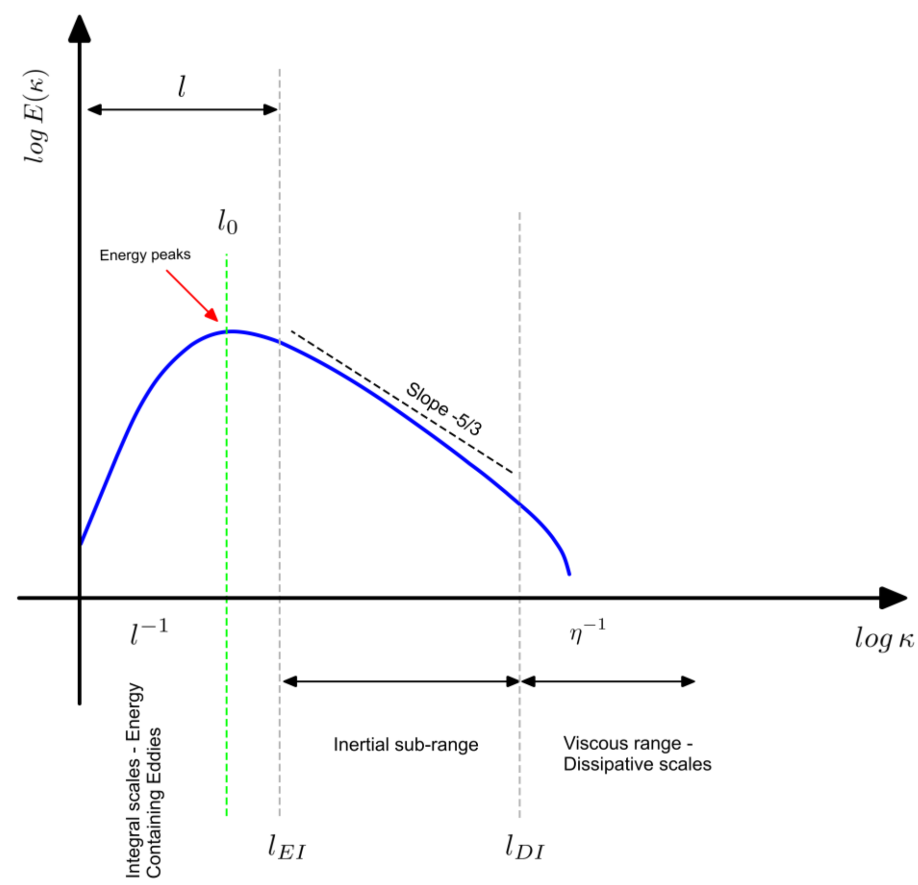
$$Re_T = \frac{k^{1/2} l_0}{\nu} = \frac{k^2}{\epsilon \nu}$$

- The turbulence and Taylor Reynolds numbers can be related as follows

$$Re_\lambda = \left(\frac{20}{3} Re_T \right)^{1/2}$$

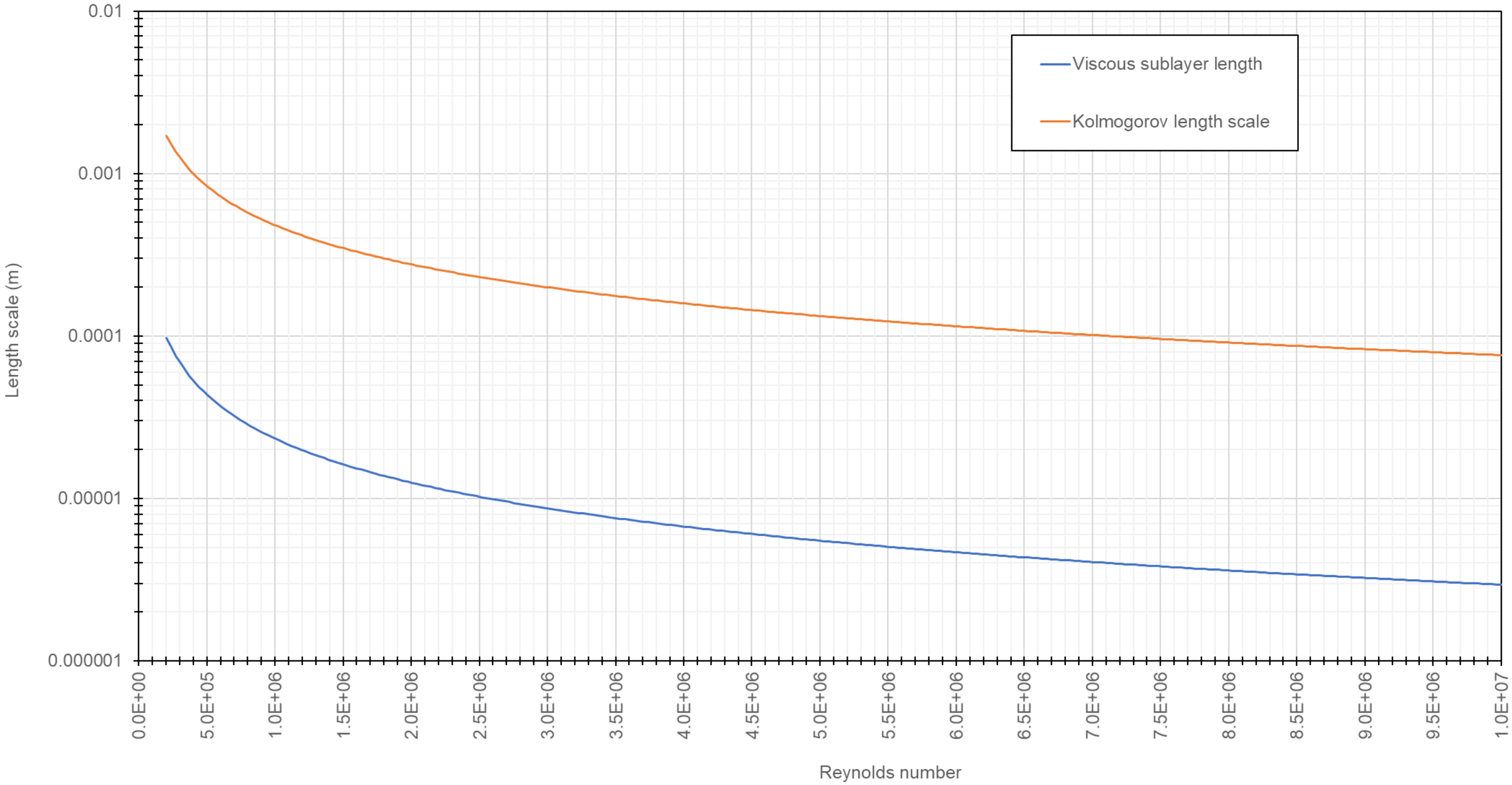
Summary of turbulence length scales

- During the previous lectures, sometimes we used the notation l_0 and sometimes we used the notation l.
  - l_0 represents the largest integral eddy.
  - l represents the average of the integral eddies.
- Some authors use l_0 and some other authors use l.
- In our explanations, we assumed that these scales are interchangeable without loss of generality.
- Have in mind that Re_T is computed using the integral scale l_0 and the TKE (related to the velocity fluctuations around the mean velocity).



Practical turbulence estimates

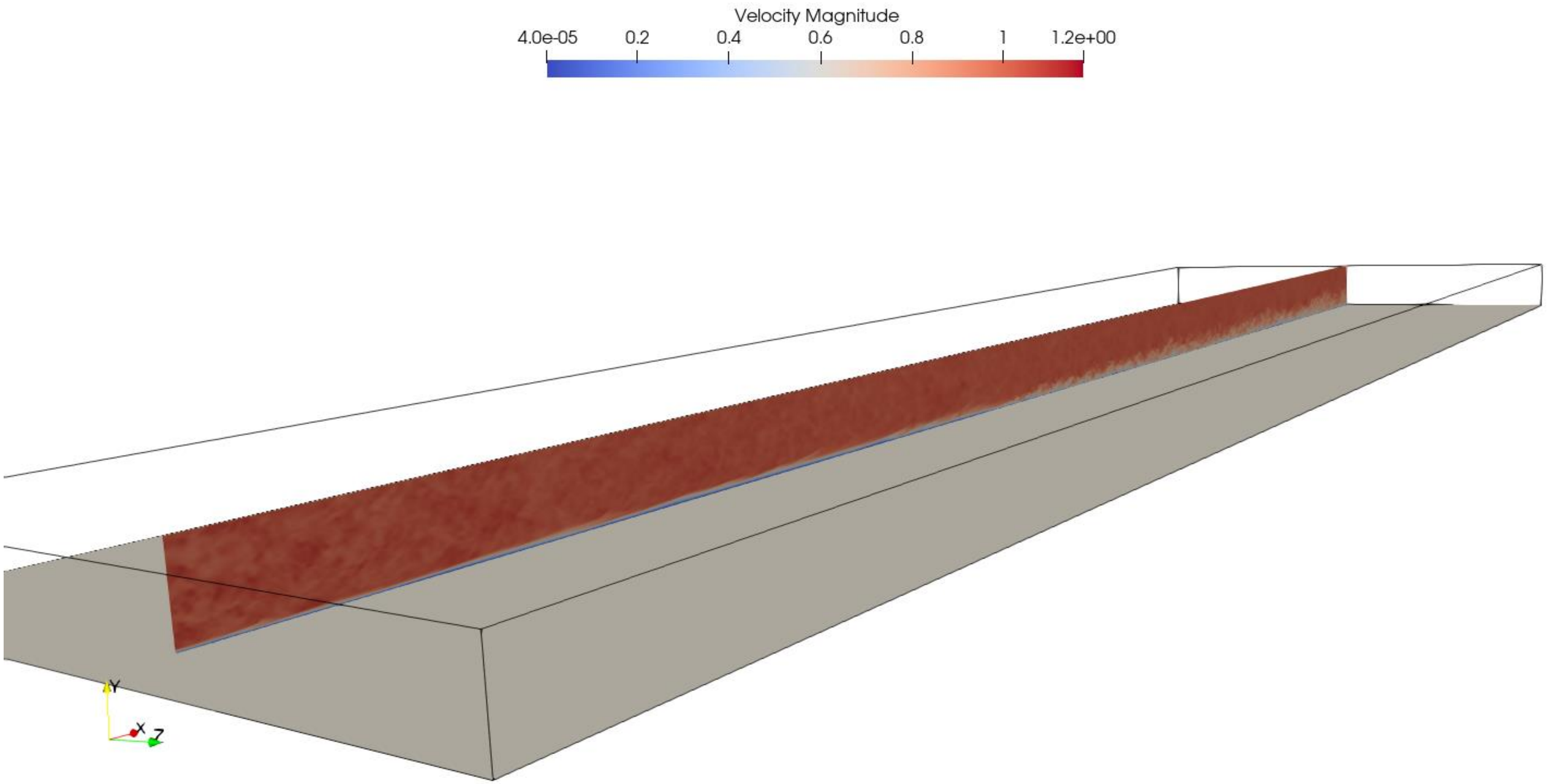
Can the Kolmogorov eddies become smaller that the viscous sublayer length?



- In a few words, no.
- In this case the viscous sublayer is always at least one order of magnitude thinner than the Kolmogorov eddies.
- The viscous sublayer cannot accommodate Kolmogorov eddies.

Practical turbulence estimates

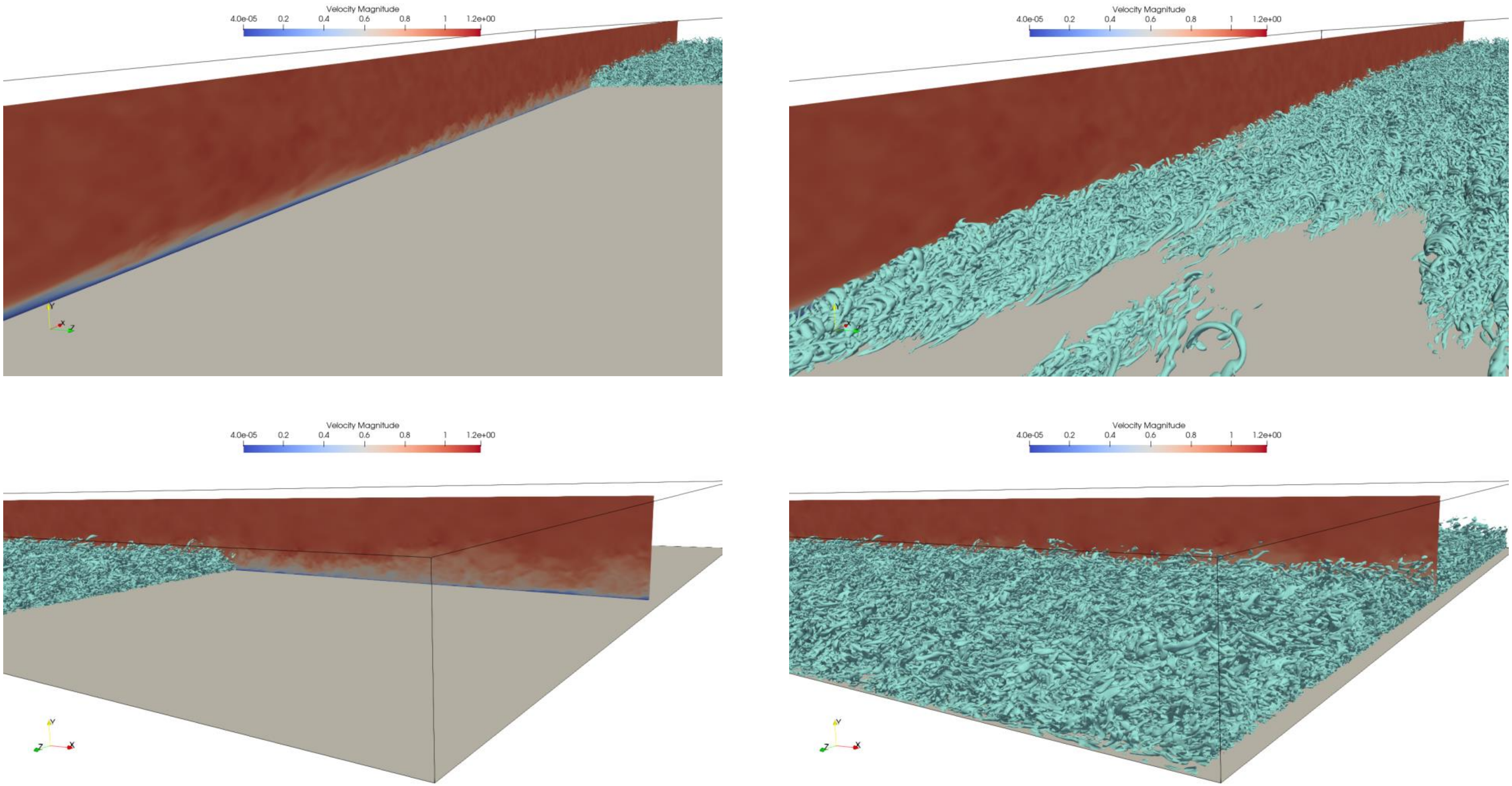
Can the Kolmogorov eddies become smaller that the viscous sublayer length?



- As dissipation takes place at the viscous sublayer, it cannot accommodate Kolmogorov eddies.
- The viscous sublayer will always adapt so it is thinner than the Kolmogorov eddies.

Practical turbulence estimates

Can the Kolmogorov eddies become smaller that the viscous sublayer length?



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Practical turbulence estimates

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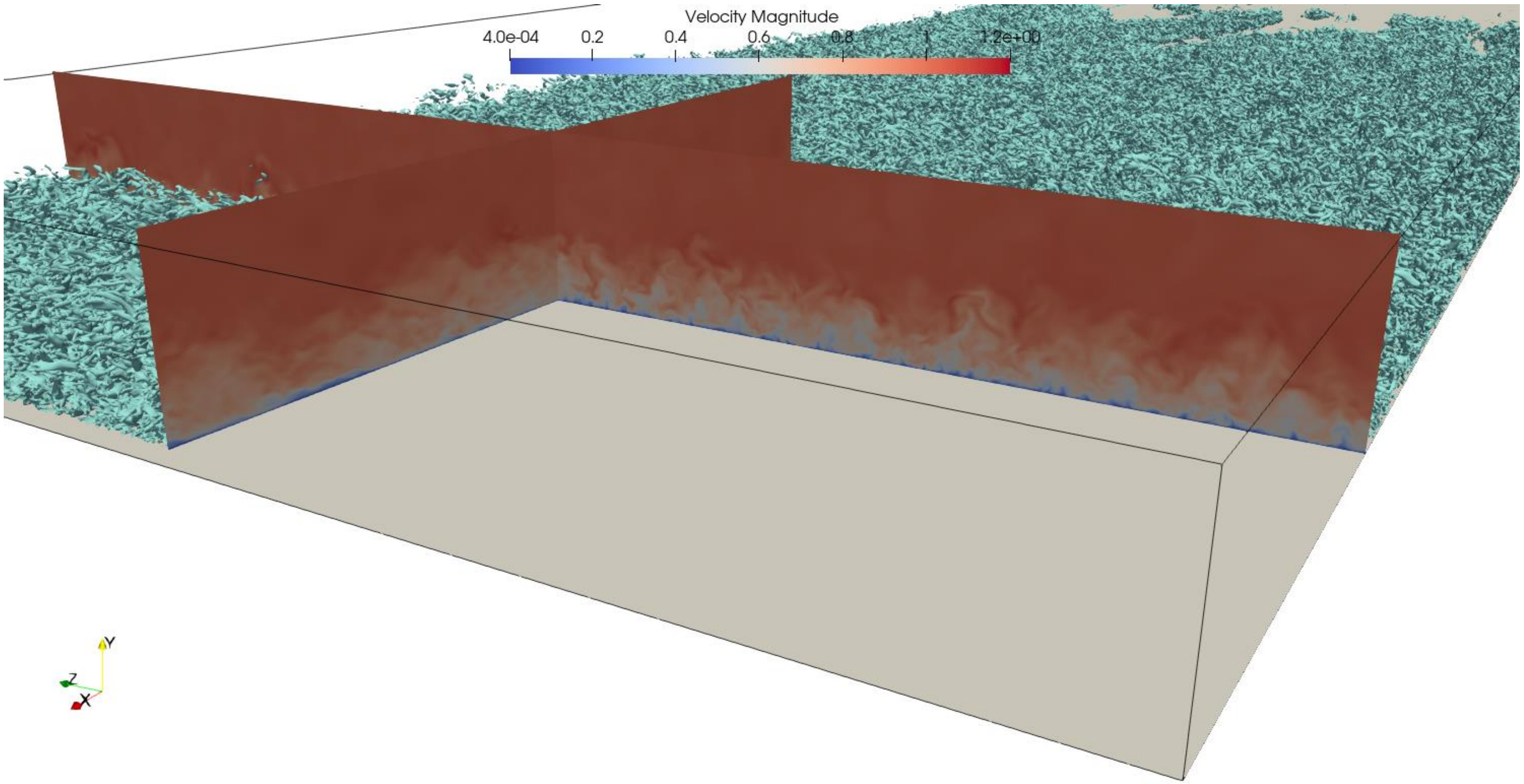

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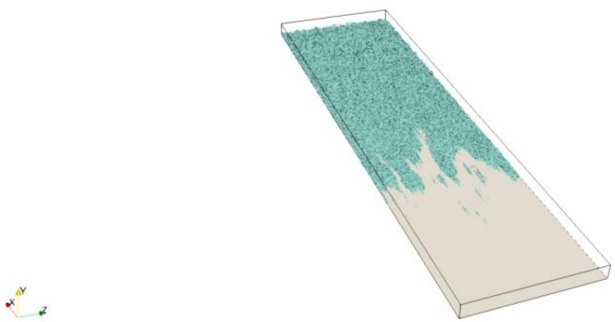
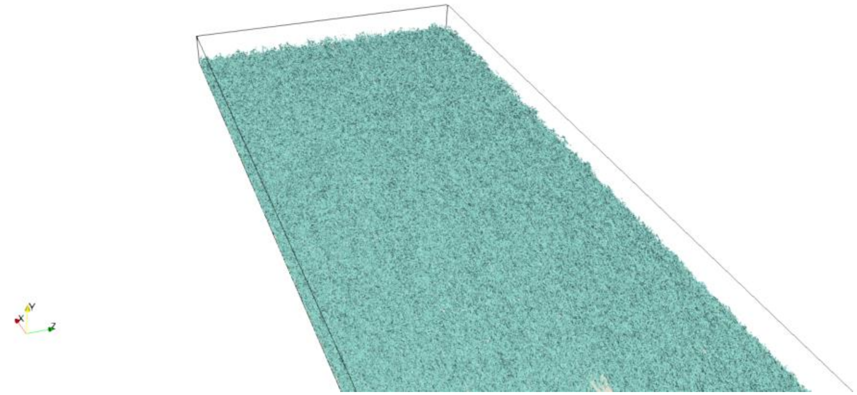
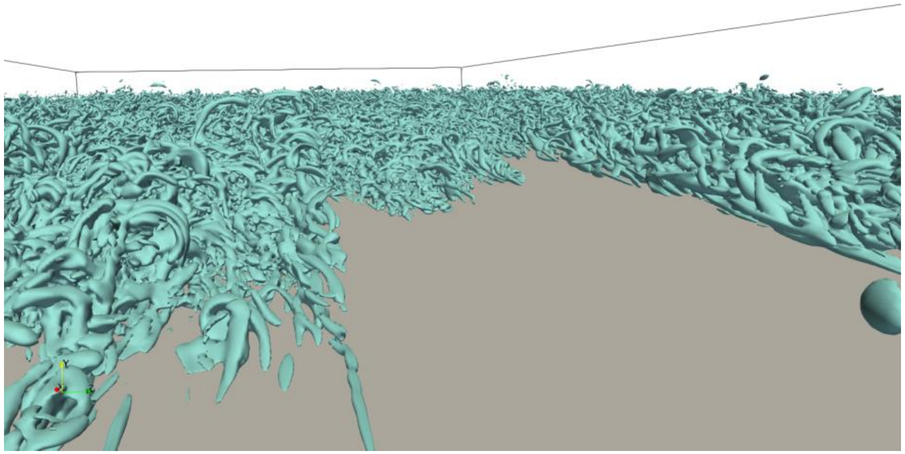
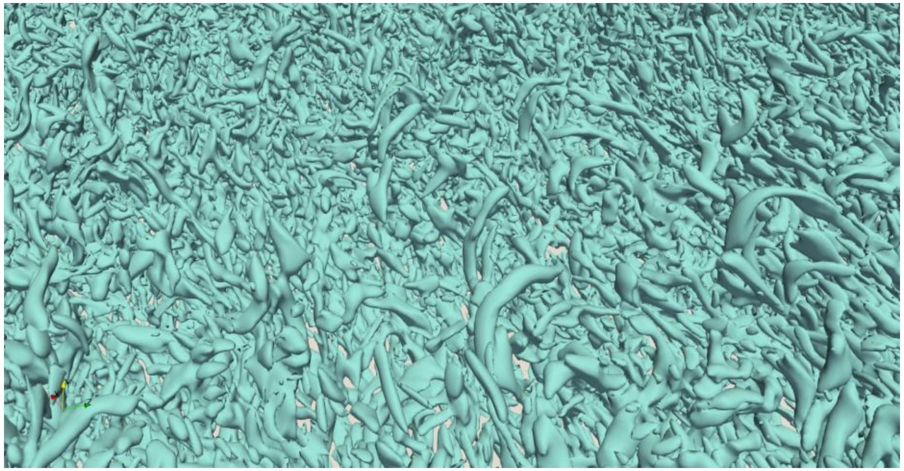
Practical turbulence estimates

Can the Kolmogorov eddies become smaller that the viscous sublayer length?









- To give you an idea how time consuming is the postprocessing of large-scale simulations:
  - We are looking at one timestep of a DNS simulation. The input file is about 17 GB, and it required about 110 GB of RAM memory, a GPU of 16 GB, 16 cores, and about 5 minutes to open and manipulate the data (mesh size approximately 1.5 billion grid points).