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CNN+LSTM Accelerated Turbulent Flow Simulation with Link-Wise Artificial Compressibility Method

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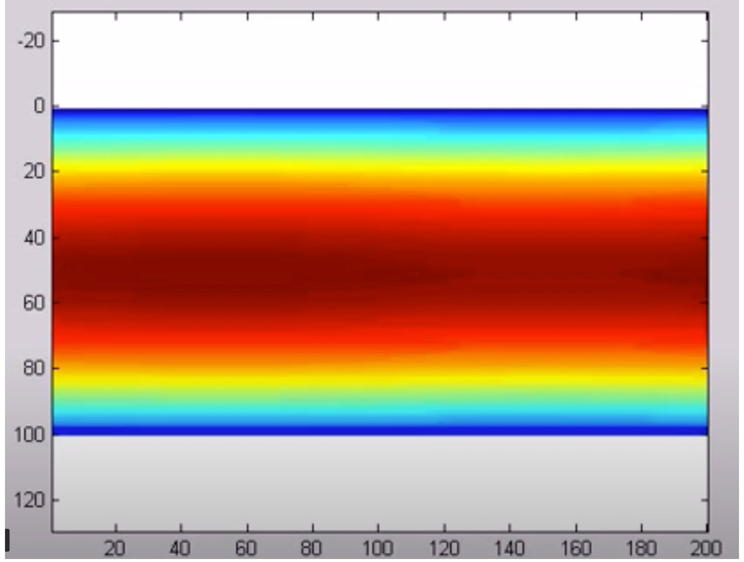
Turbulent Flow

- Turbulent flow is ubiquitous in nature.
- Turbulent flow is complex and one of the unsolved problems in Physics.
- Transition to Turbulence:

Need **very long time** to get the fully developed turbulent flow!

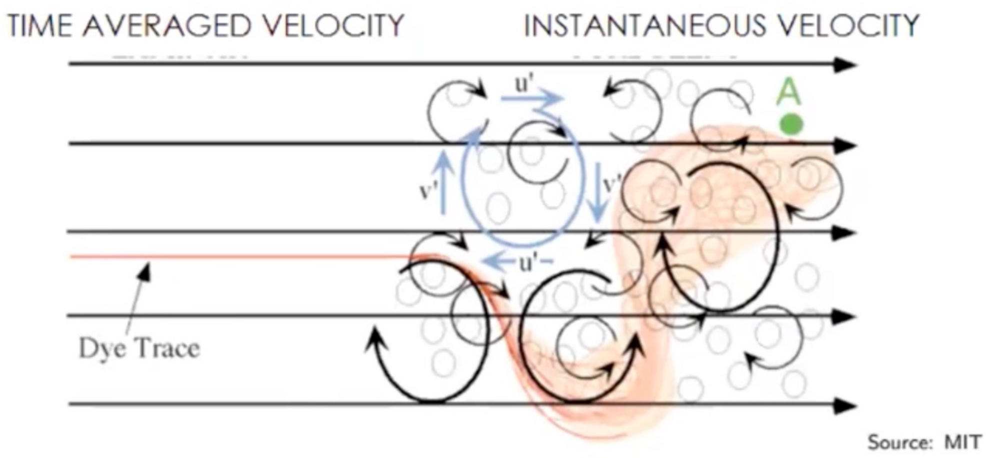


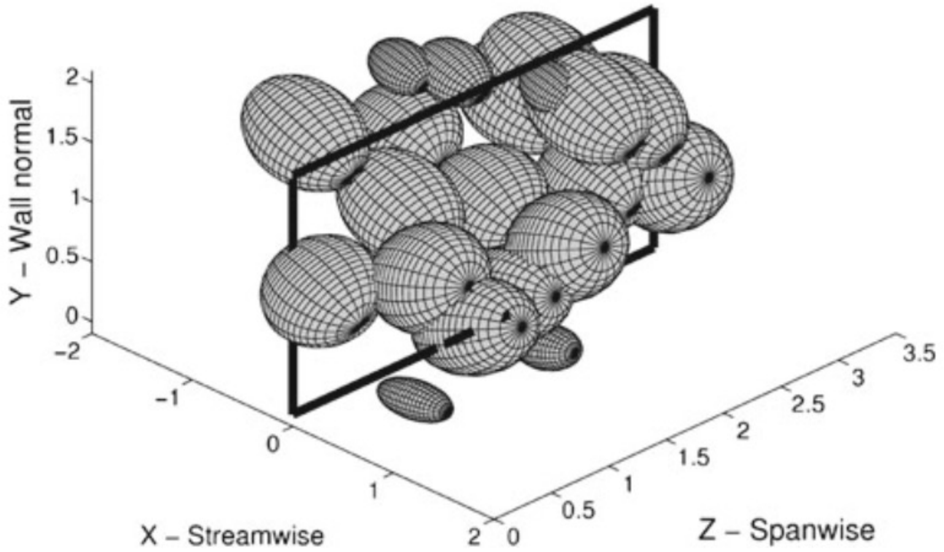
Transition to turbulent flow on channel[2]

[2] https://www.youtube.com/watch?v=lAt1DF-esDI.

Synthetic Eddy Method (SEM)

- Turbulent flow is composed of mean velocity and fluctuation velocity.
- SEM defines a fixed number of synthetic eddies.





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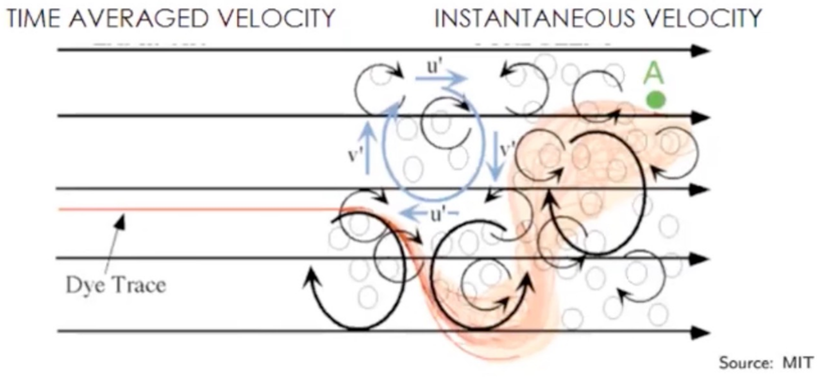
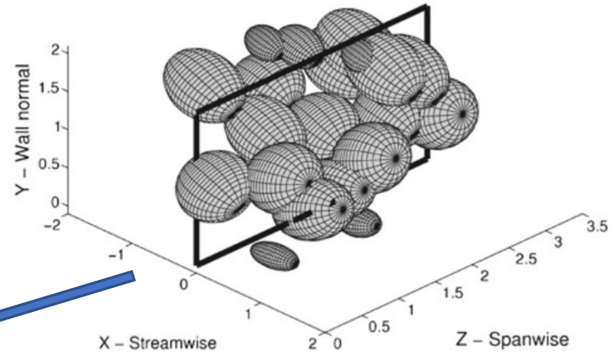
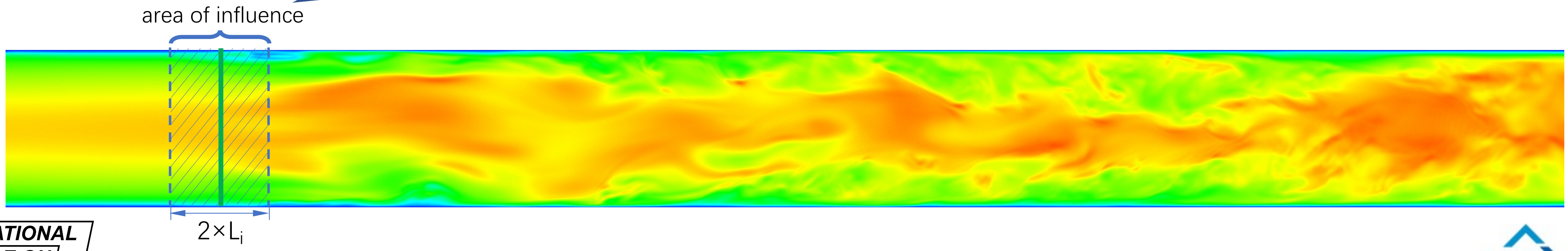
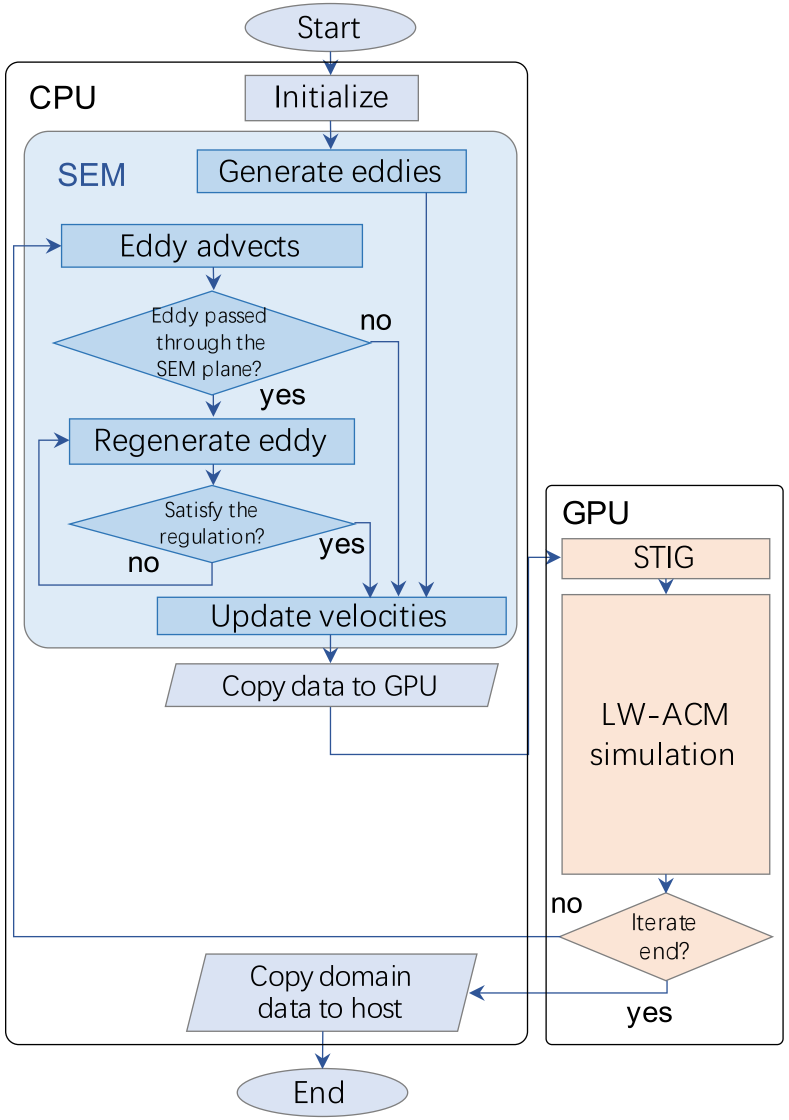






Synthetic Eddy Method (SEM)

- SEM is run on CPU
- Simulation of the main domain is executed on GPU
- SEM updates the velocity iteratively



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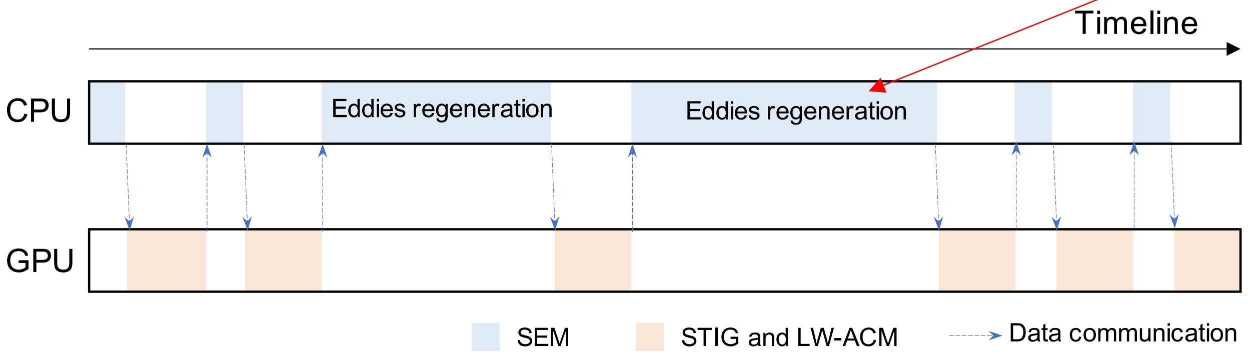

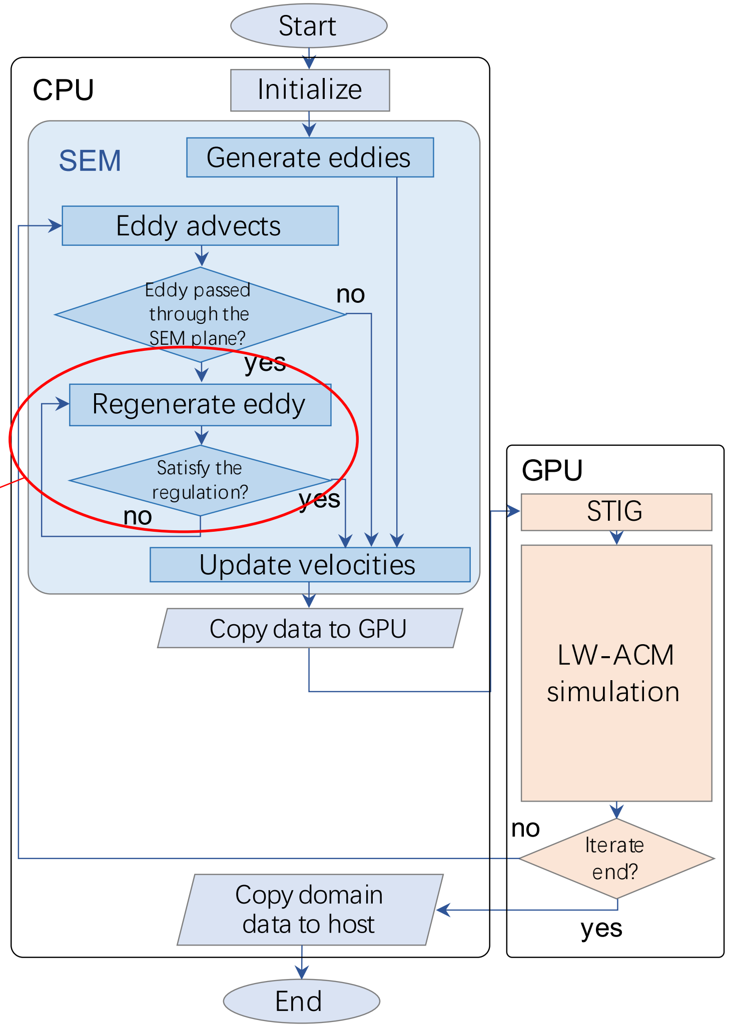

Inefficient GPU usage!

Synthetic Eddy Method (SEM)

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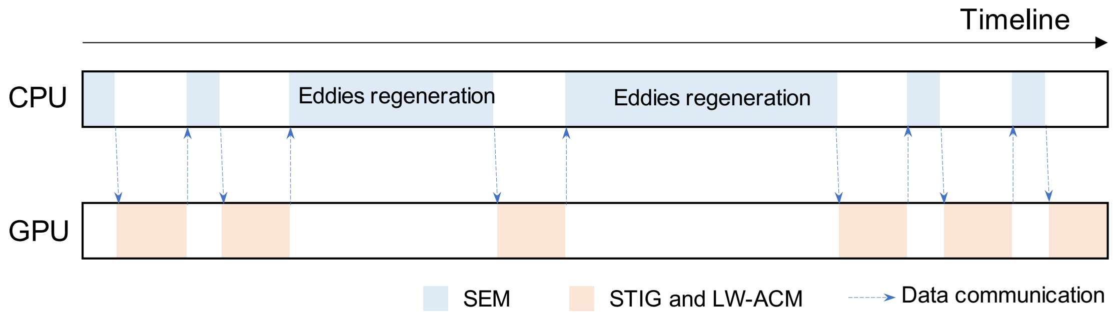
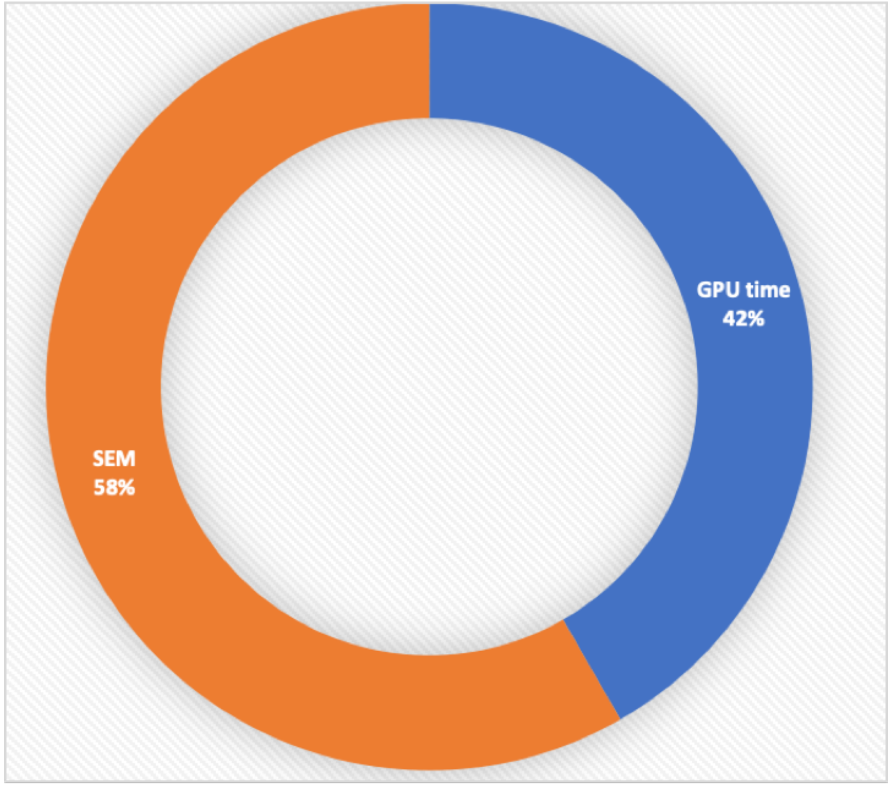
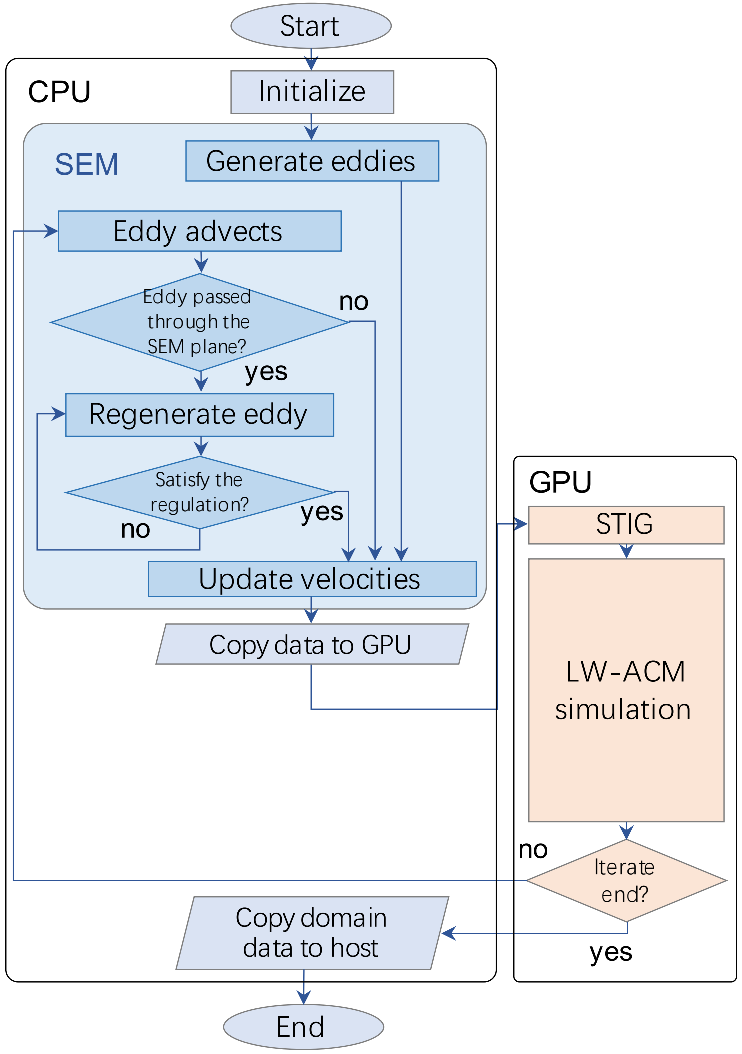




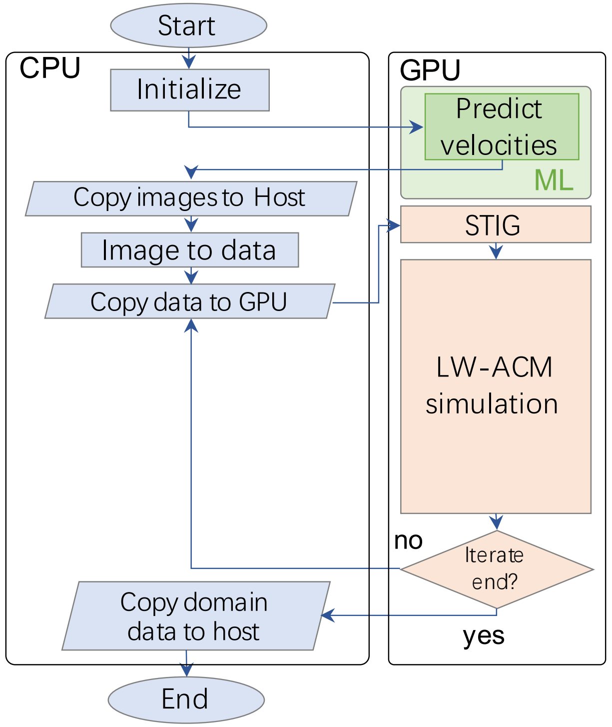
- As the inlet boundary condition, SEM takes about **58%** of the whole computational time
- Needs to be improved!

Flow Chart



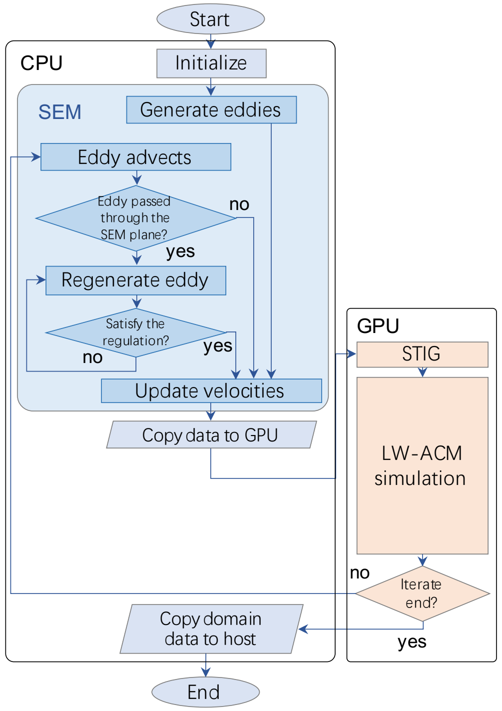
SEM generates turbulent inflow

Replace SEM with Machine Learning

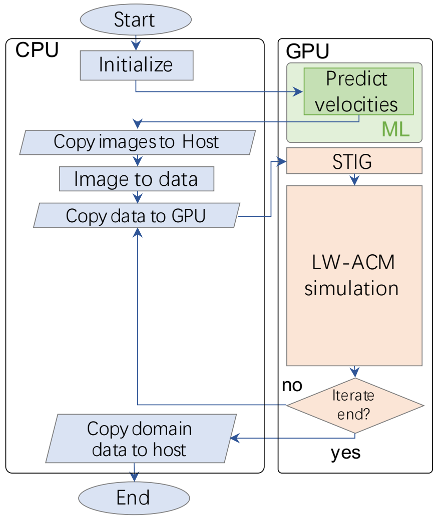


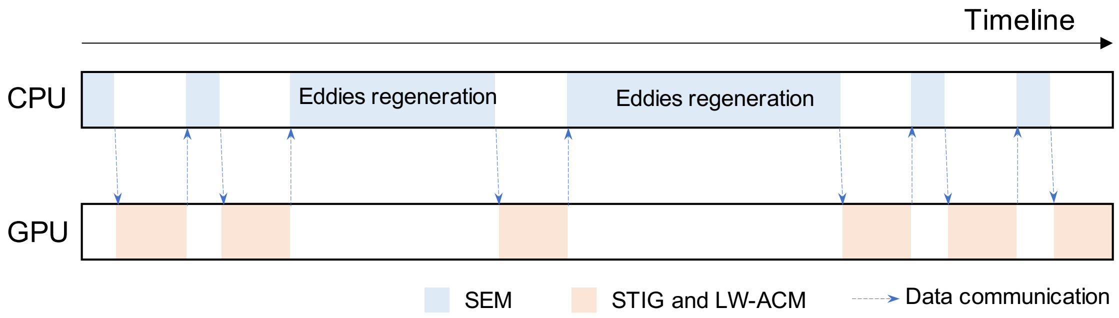
Machine learning generates turbulent inflow

Flow Chart

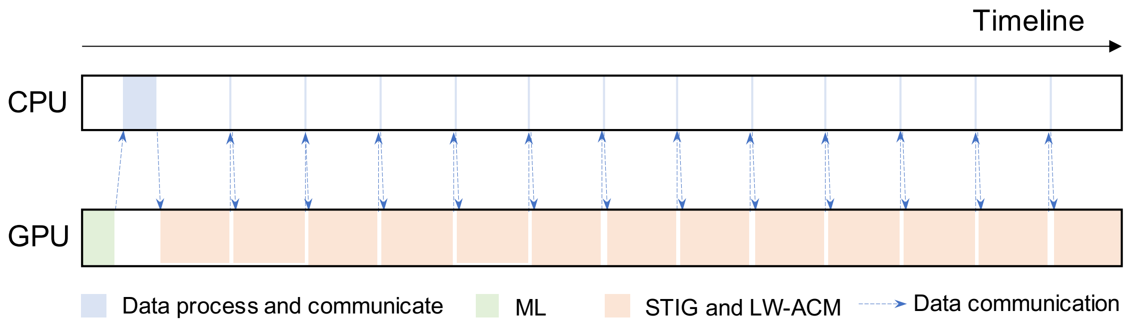


Replace SEM with Machine Learning





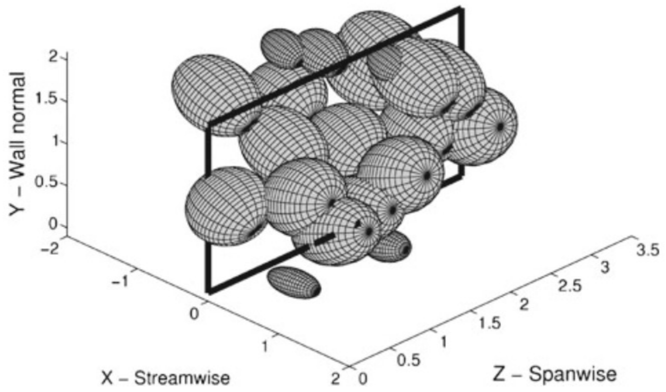
SEM generates turbulent inflow



Machine learning generates turbulent inflow

Training Data

SEM generates the fluctuating velocity by eddy advection

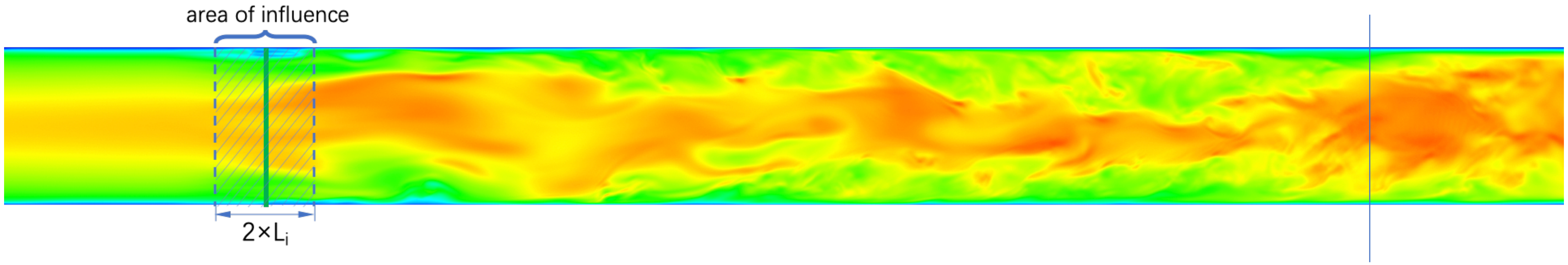


- SEM assumes:
  1. the eddies advect only in x direction
  2. the shape of the eddies is constant

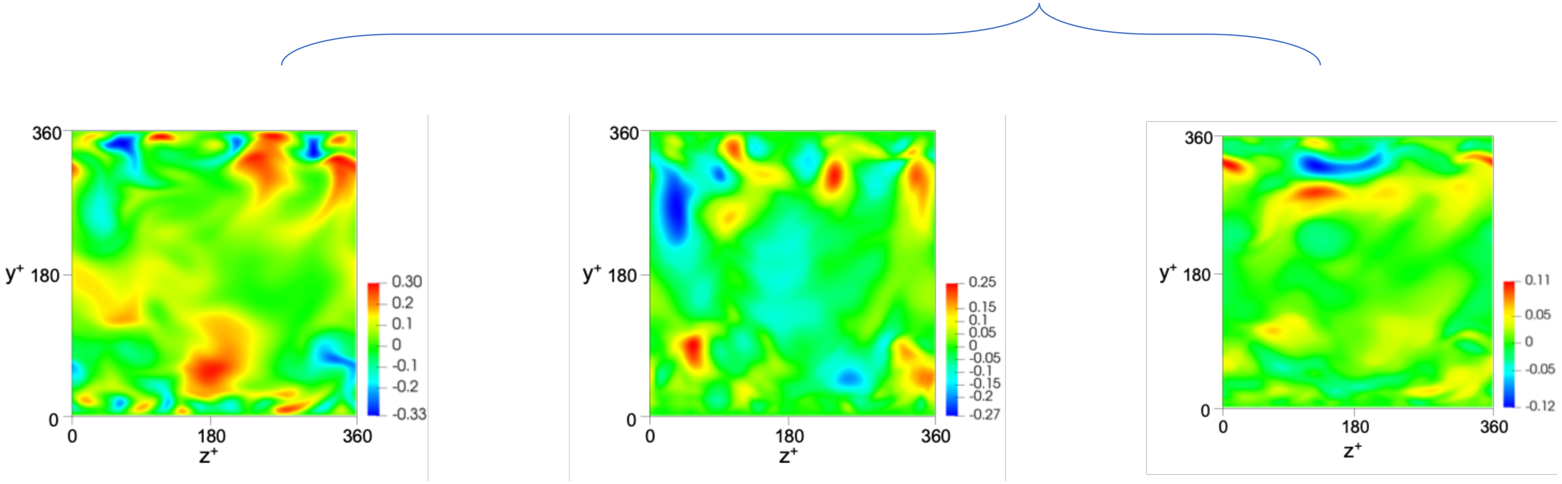
- However, in fact:
  1. The eddies moves in every directions
  2. The eddies may be rotated, stretched …

Training Data

Generating the training data from downstream

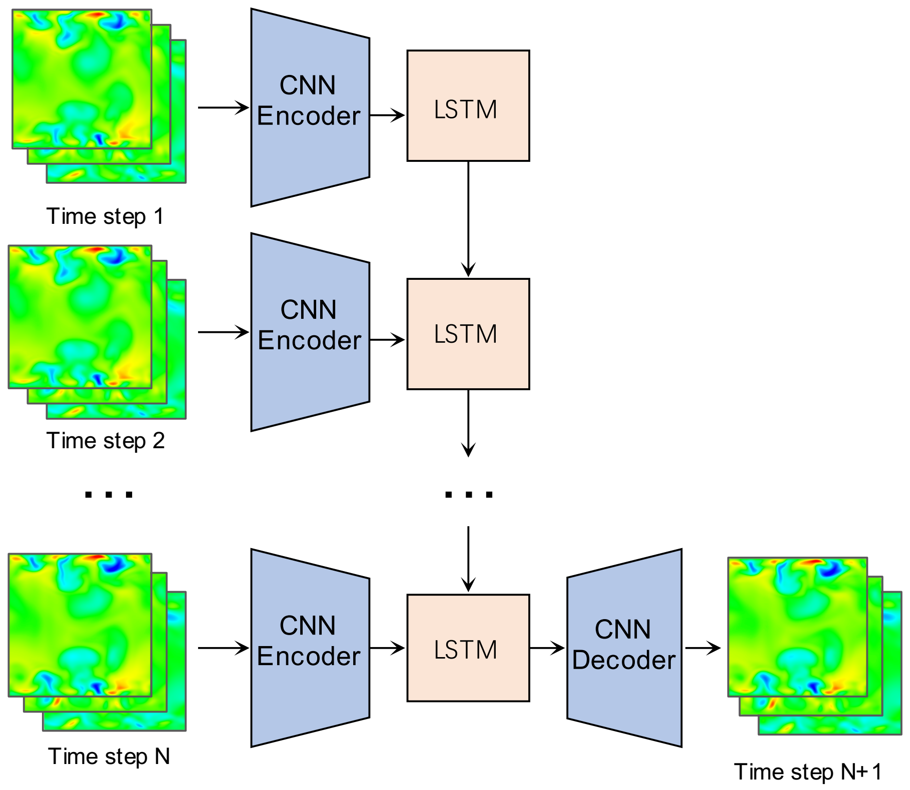


- Training data from 5 million timesteps
- Interval is 500 time steps



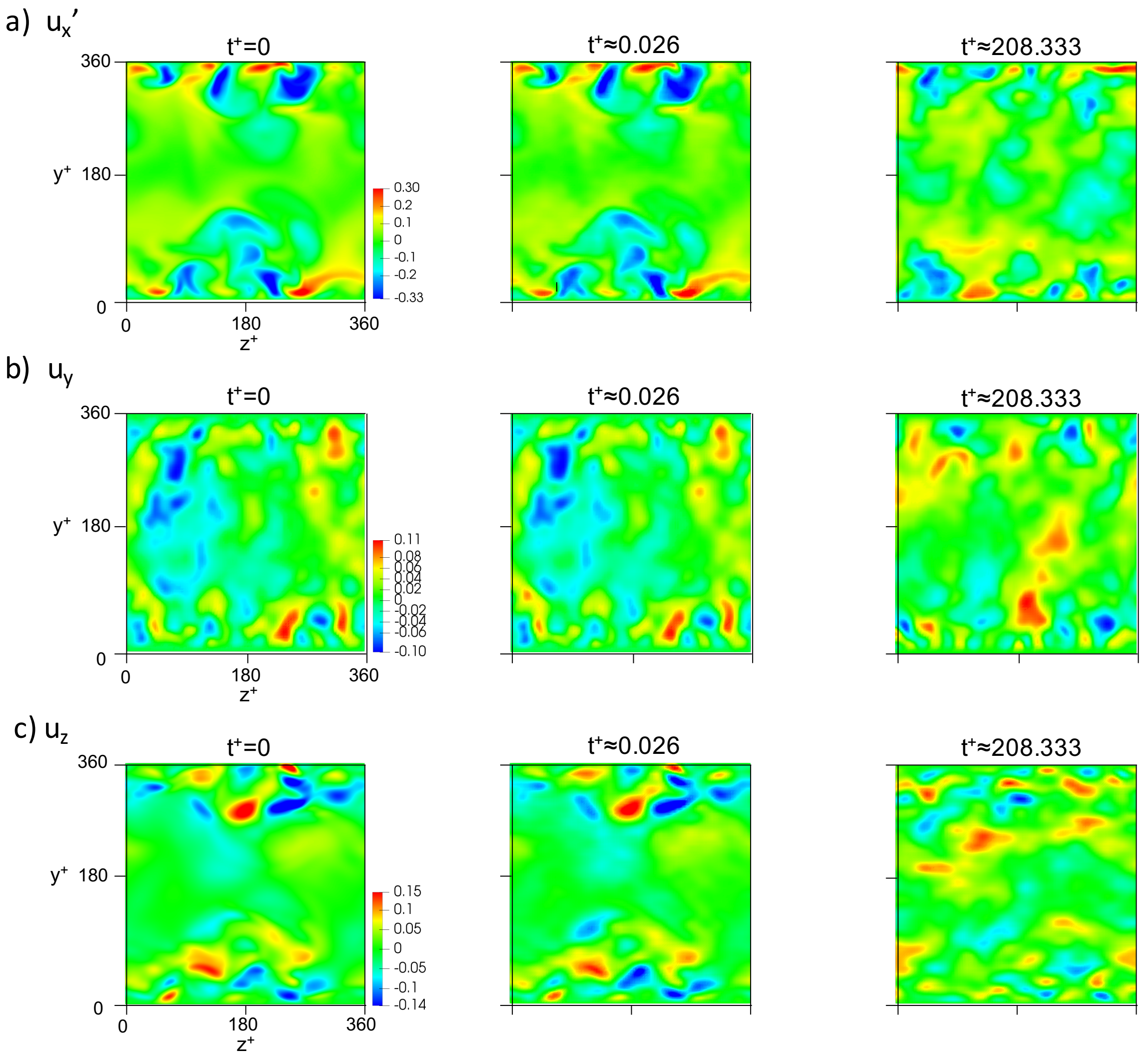
CNN+LSTM Architecture

- Input: data from 5 continuous time steps
- Output: data at next time step
- Only the original data at first 5 time steps are needs as the initial input
- After that, the input data will be obtained from the previous predicted data



Predicted Results

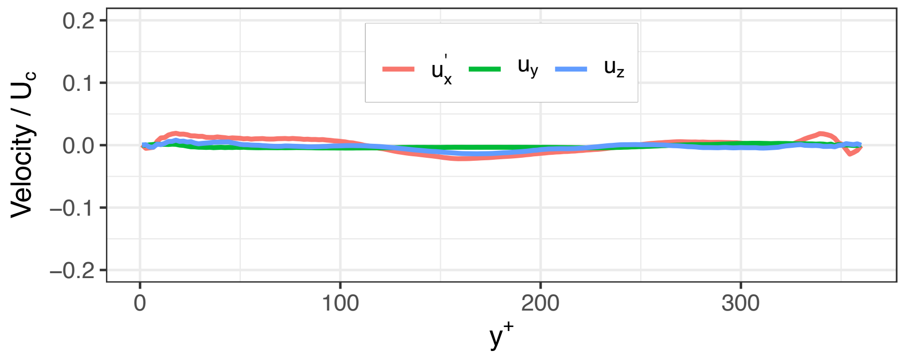
- First column: training data
- Second and third column: predicted data after 500 timesteps and 4,000,000 timesteps, respectively



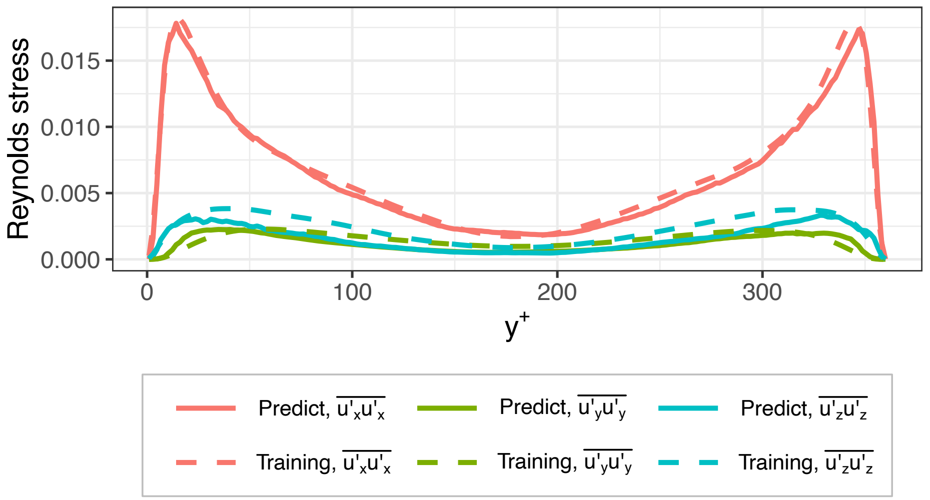
However, it is hard to measure the results from the **instantaneous data**. The common validation method is to **time-average** the instantaneous data.

Predicted Results

Time-averaged results



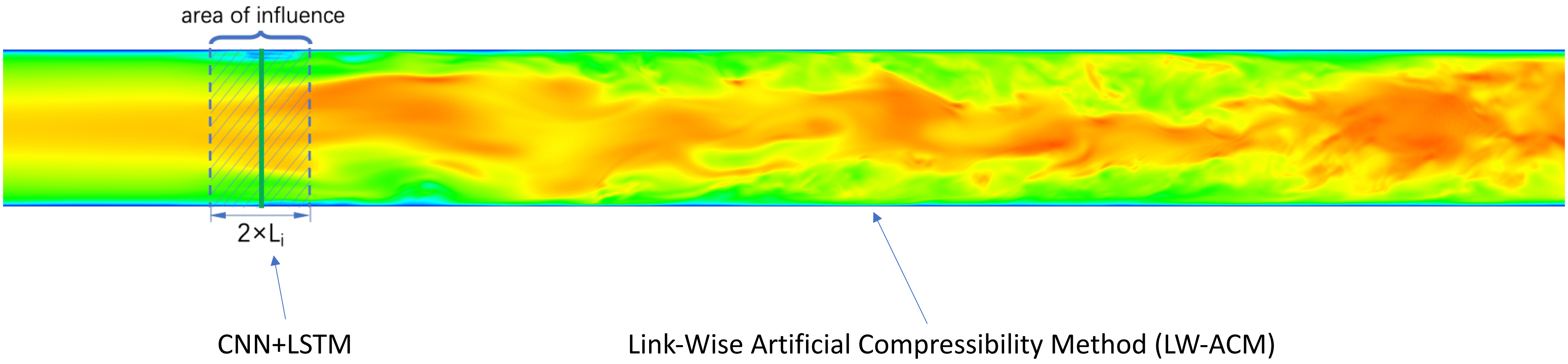
Time-averaged velocity



Time-averaged Reynolds Stress

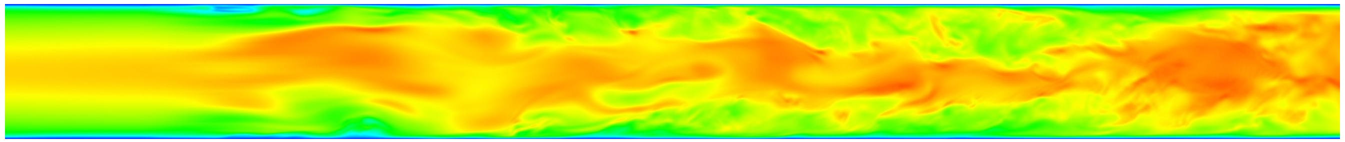
Apply ML into channel

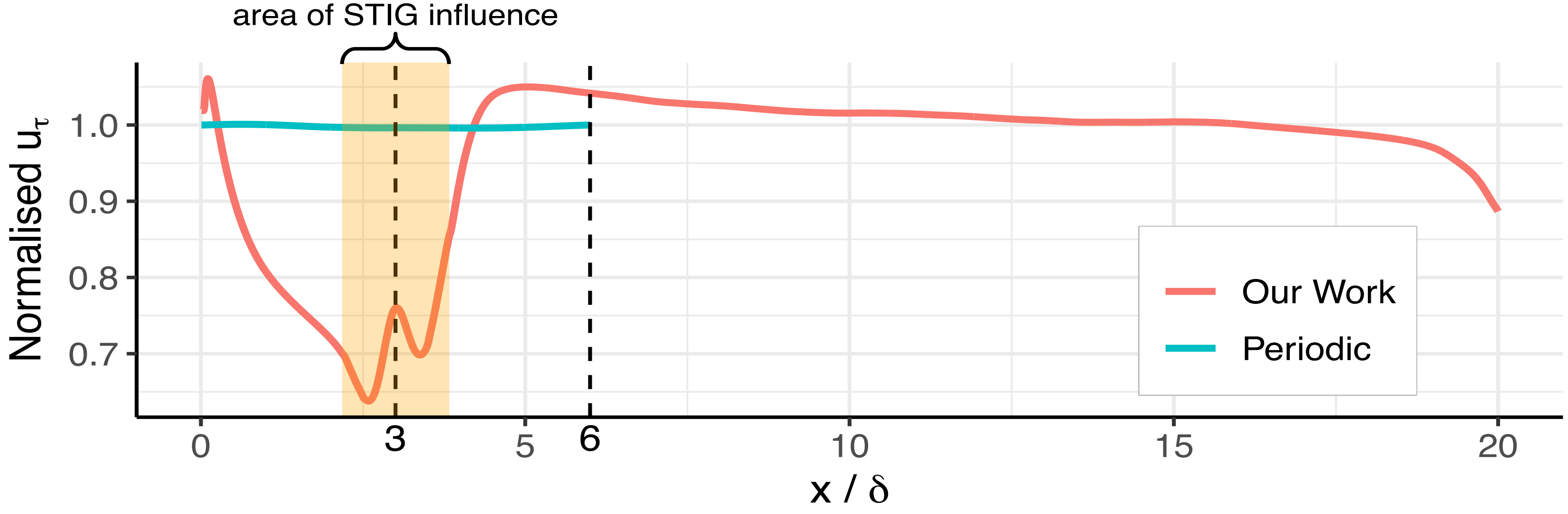
- The whole channel domain is simulated by LW-ACM
- CNN+LSTM generates the turbulent inflow



Simulation Results

Friction velocity





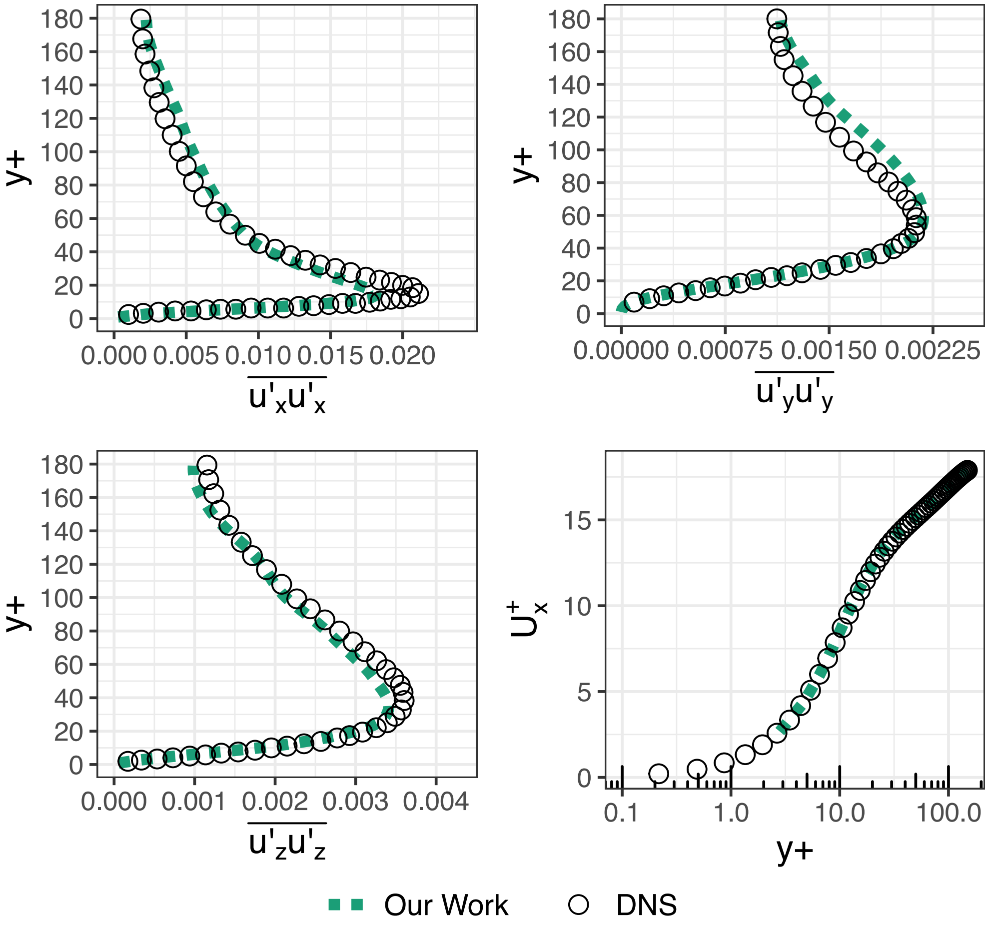
Friction velocity

- The fluid gradually become fully developed turbulent flow downstream.

Simulation Results

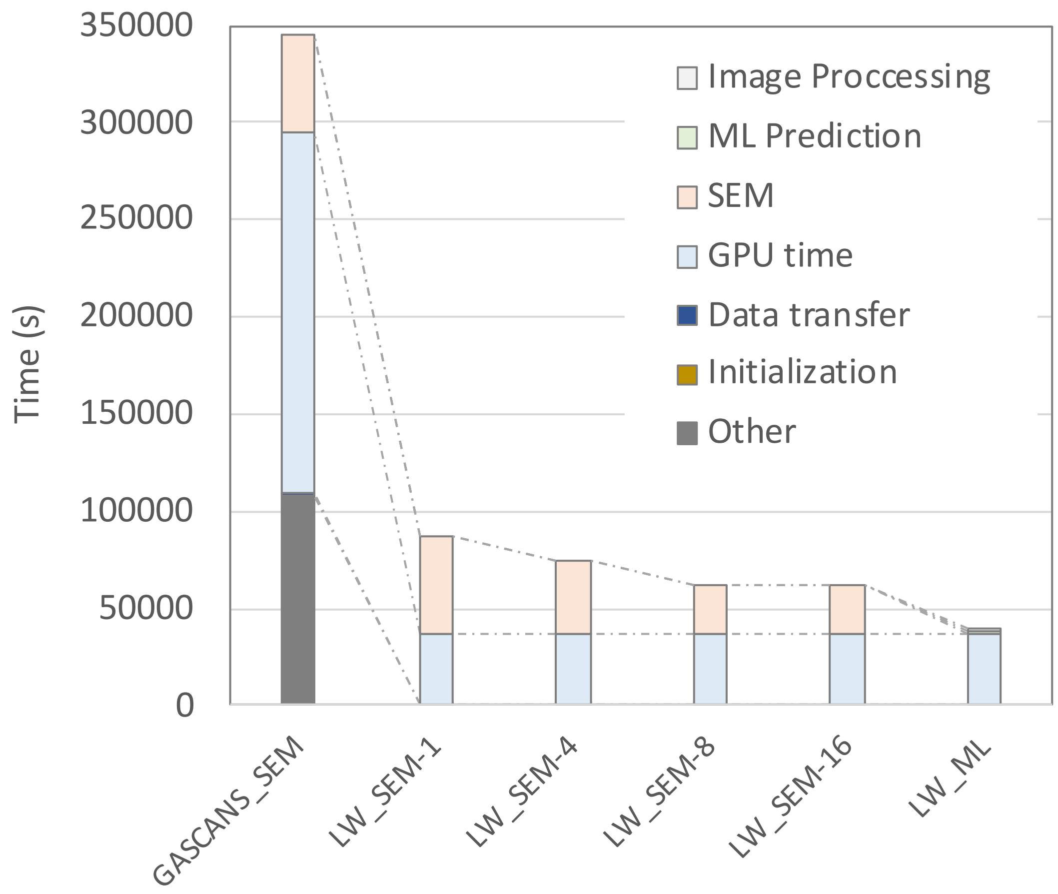
Time-averaged results

- We time-averaged the results at the channel flow downstream
- The Reynolds stresses and the streamwise velocity are close to DNS



Time-averaged Reynolds stresses and streamwise velocity

Performance



- We cannot benefit from the OpenMP when more than 16 threads are used.
- Machine learning outperforms 15X than SEM.
- Our work halves the whole computational time.
- Compared to GASCANS, this work is 8X faster.

Performance

	RANS	DDES	GPU-LBM (GASCANS)	Our work
resource	120 CPU	288 CPU	8 CPU + 1 GPU	**1 CPU + 1 GPU**
Mesh (million)	～3	8.3	17.5	70.8
time/DDES time	0.1	1	0.27	0.053

- This work is based on 1 CPU + 1 GPU.
- To our best of knowledge, the existing commercial or opensource software, such as OpenFOAM, Palabos, OpenLB, Sailfish, GASCANS, LUMA, cannot get the same performance under the same hardware. (Most of them even cannot simulate the same scale due to the memory size.)

Conclusion

- We design a novel CNN+LSTM turbulent inflow generator to replace SEM as the inlet boundary condition
- We introduce CNN+LSTM as a source term into STIG to make it work with LW-ACM
- We combine machine learning and LW-ACM to achieve fast turbulent flow simulation
- We evaluate our system in extensive experiments that demonstrate our turbulent inflow generator is over 15X faster than SEM
- We show our work is the fastest turbulent channel flow simulation with turbulence inlet to date

Thanks you for listening!

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