Tackling Complex Flow Problems via Numerical Simulation
From Jumping Fish & Heart Valves to River Flooding and Wind Energy

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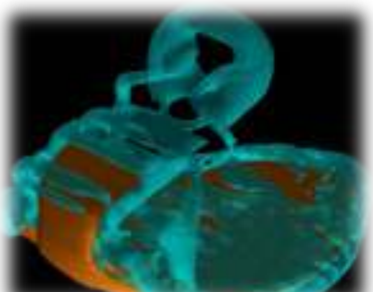
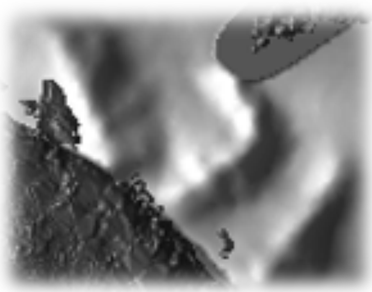
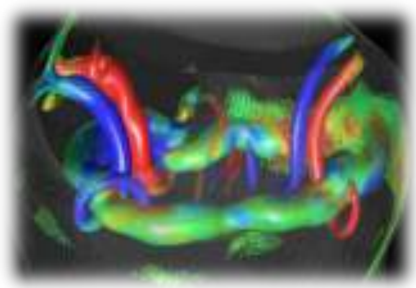
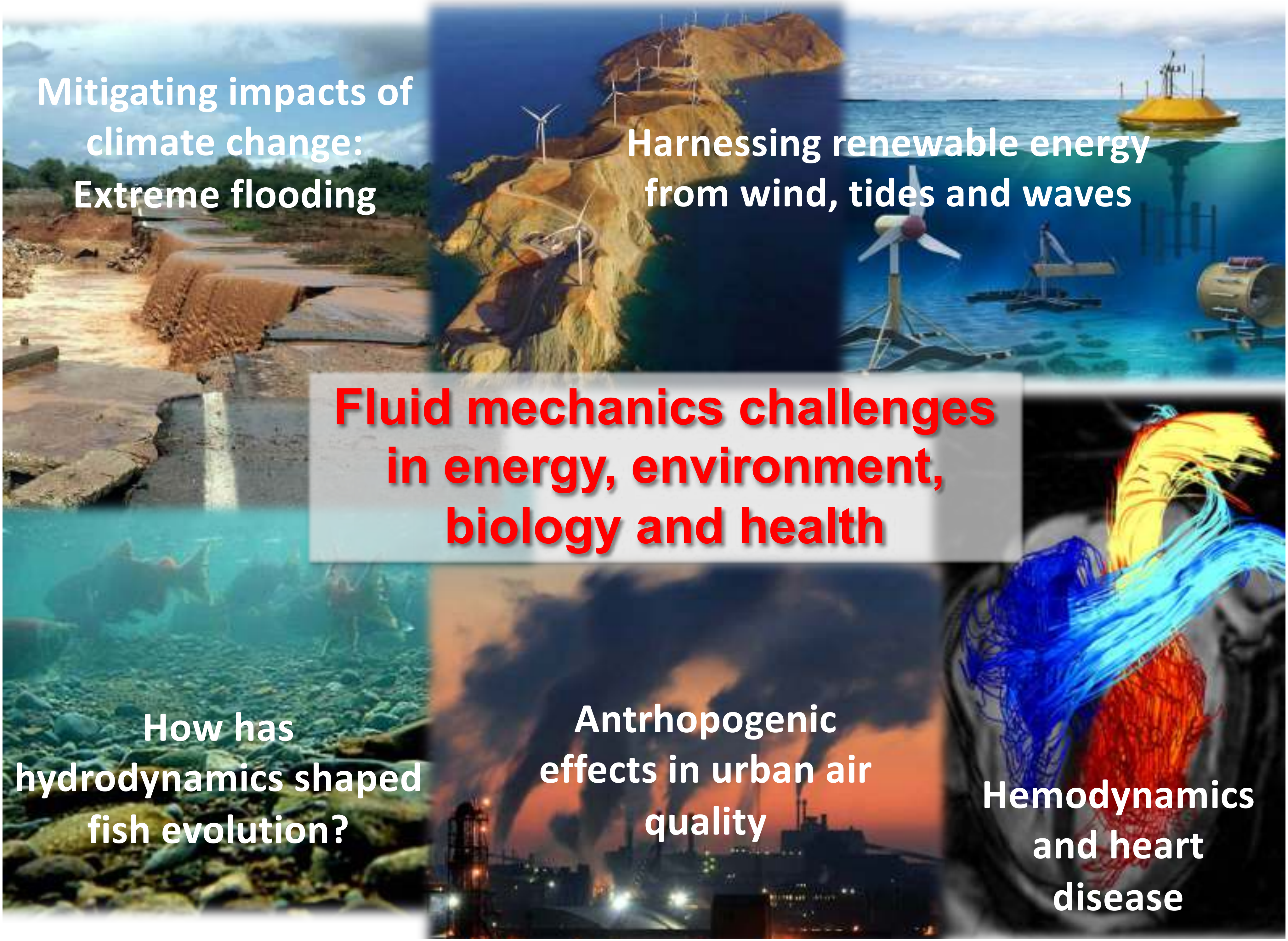
Stony Brook, NY

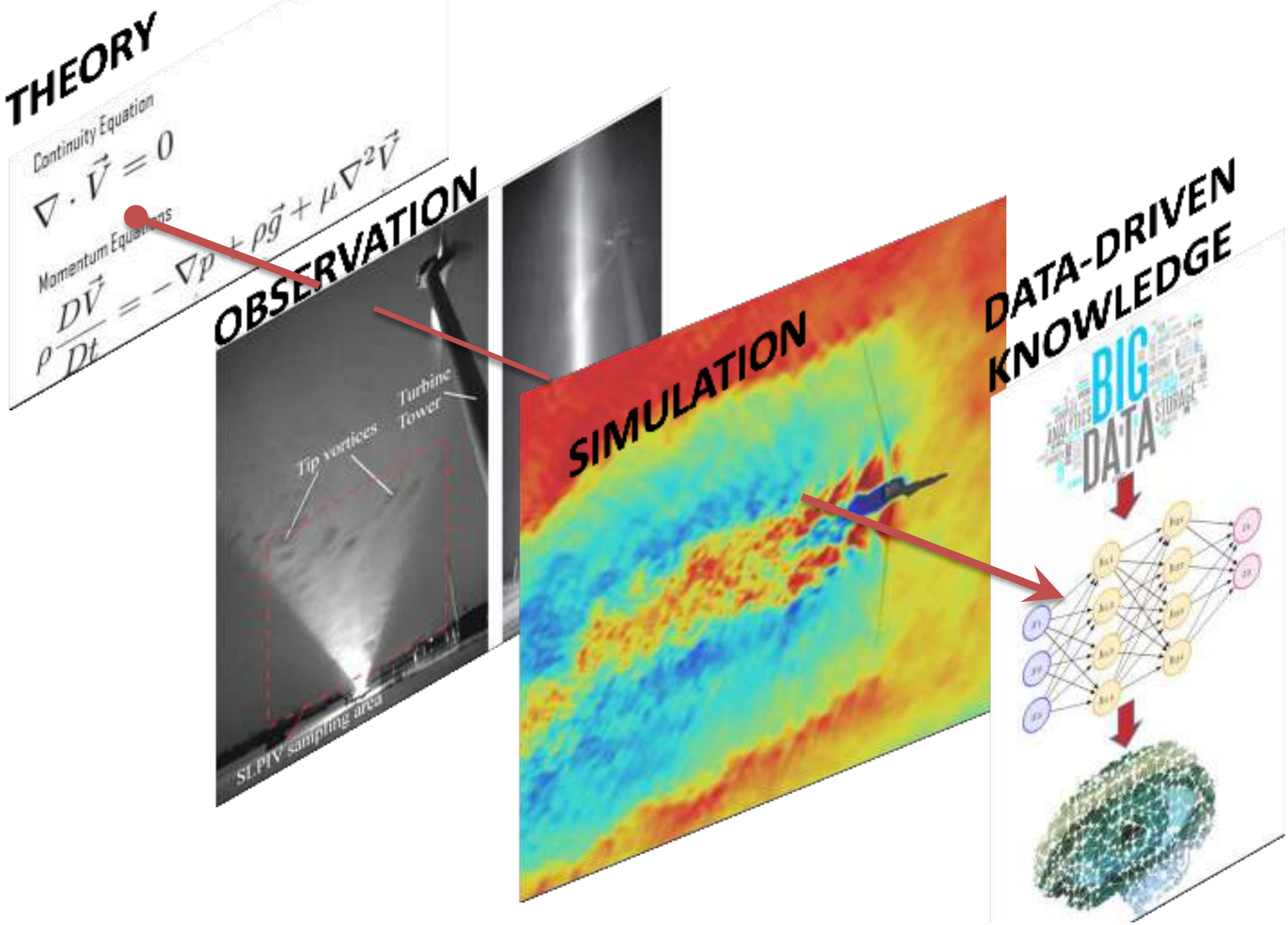
FAR BEYOND

NYU Tandon School of Engineering Dean’s Lecture
November 22, 2019

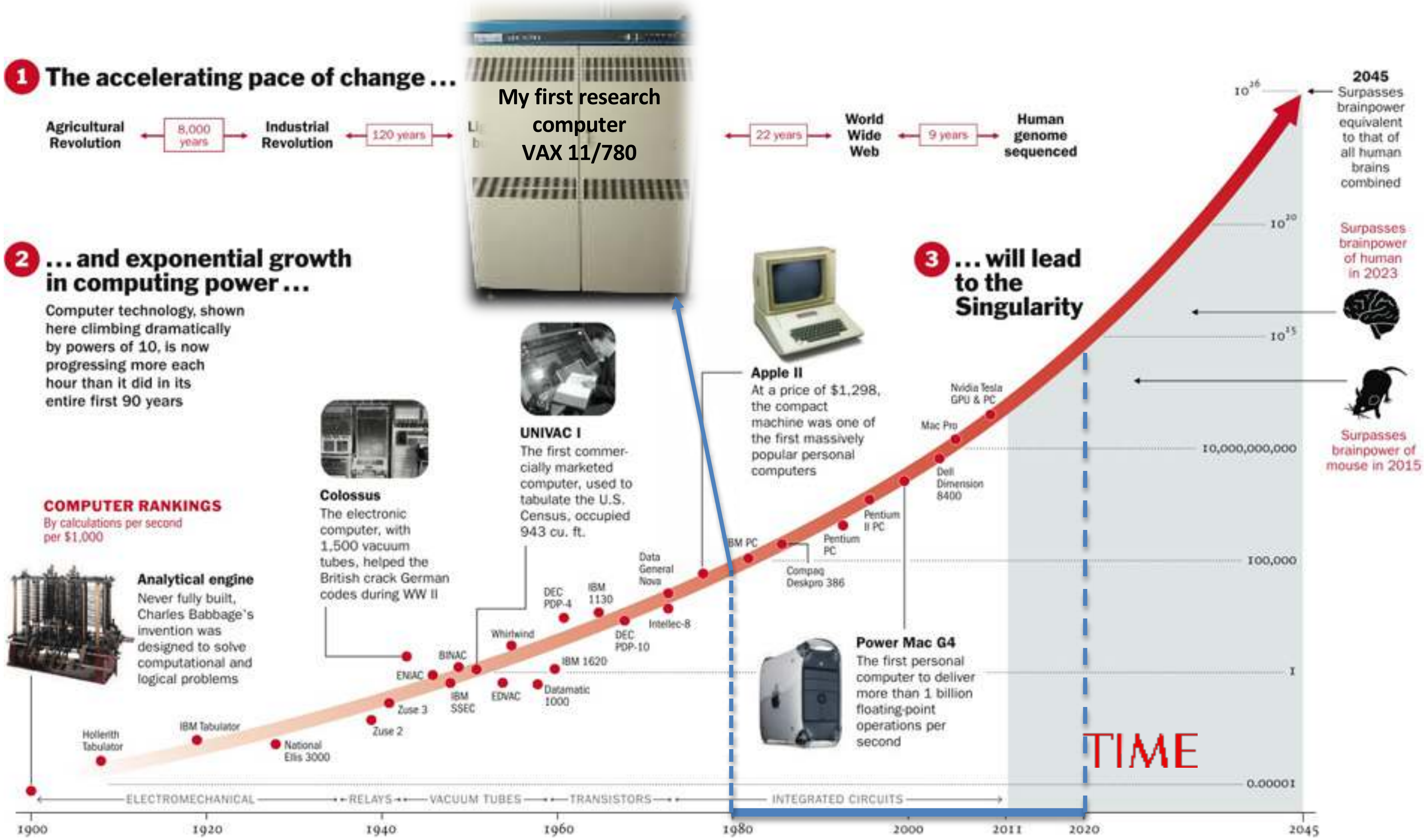
Stony Brook University
College of Engineering and Applied Sciences


Mitigating impacts of climate change: Extreme flooding
Harnessing renewable energy from wind, tides and waves
Fluid mechanics challenges in energy, environment, biology and health
How has hydrodynamics shaped fish evolution?
Antrhopogenic effects in urban air quality
Hemodynamics and heart disease

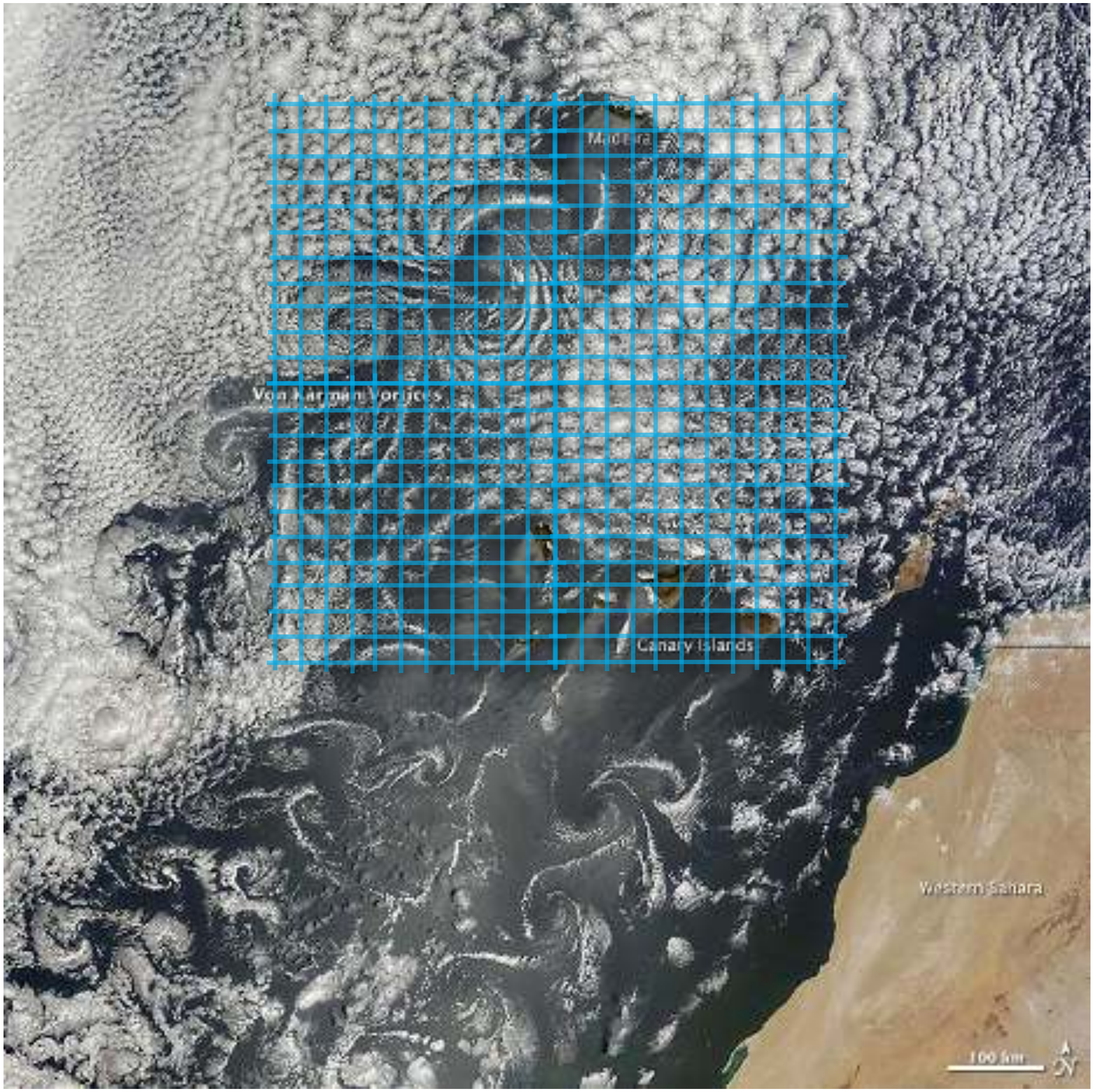
The Pillars of Scientific Inquiry



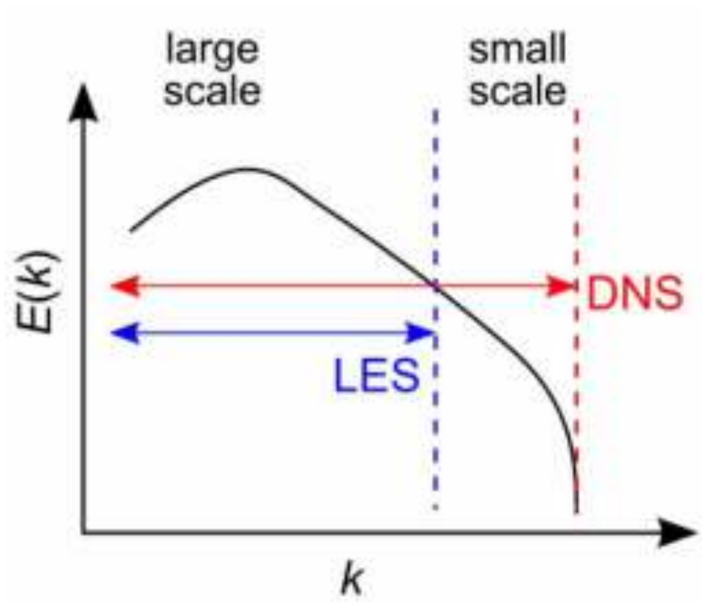
Exponentially Growing Computing Power



Most flows in nature are turbulent



Size of relevant eddies can range from $O(10^3 m)$ to $O(10^{-4} m)$

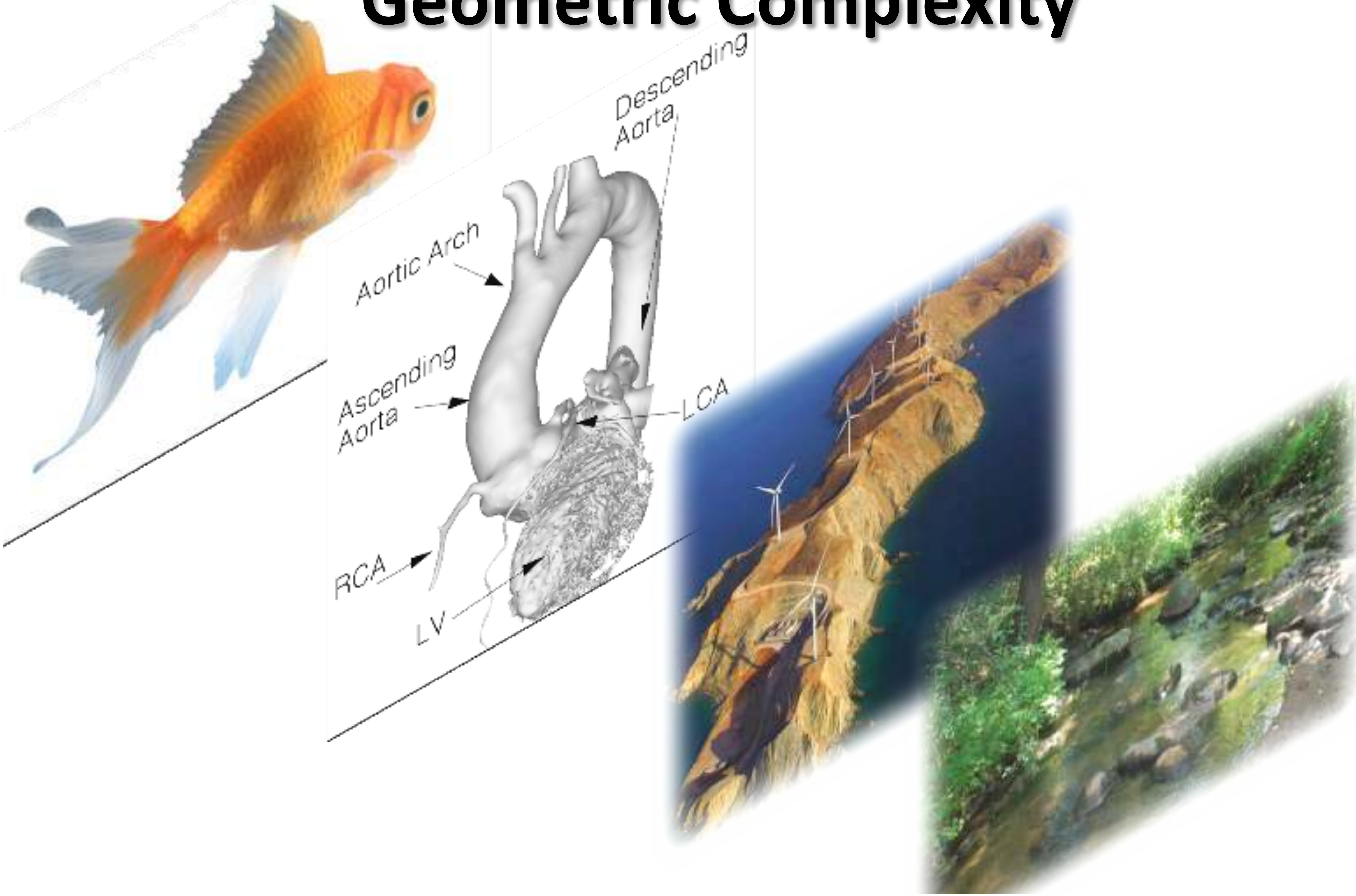


Large Eddy Simulation (LES)

vs

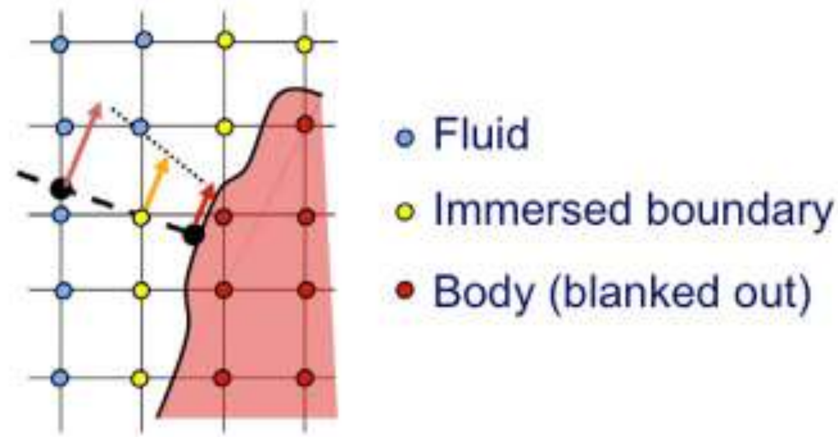
Direct Numerical Simulation (DNS)

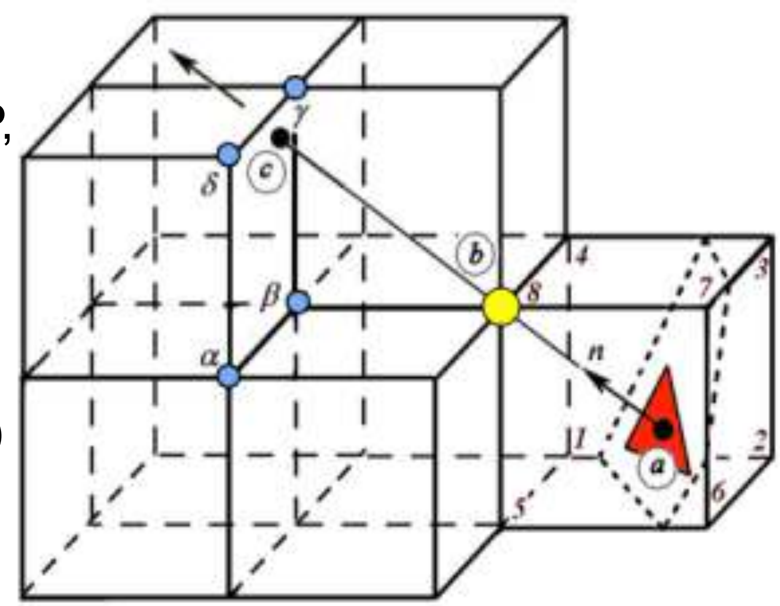
Multi-Physics Phenomena & Arbitrary Geometric Complexity



Virtual Flow Simulator®: Large Eddy Simulation of turbulence in real-life flows

- Sharp Interface Immersed Boundary
- Wall model to reconstruct velocity field at IB nodes
- 2nd order central differencing on a hybrid staggered/non-staggered grid
- Fractional-step algorithm: Jacobian-free Krylov solvers with Algebraic Multigrid
- Turbulence simulation and modeling:
  - ✓ Direct Numerical Simulation (DNS)
  - ✓ Large Eddy Simulation (LES)
- **Fluid-structure interaction** (Borazjani et al., JCP, 2008; Gilmanov et al., J. Comp. Phys 2015)
- **Level sets for free-surface modeling** (Kang & Sotiropoulos, J. Hydr. Eng., 2015)
- **Coupled hydro-morphodynamics** for sediment transport (Khosronejad & Sotiropoulos JFM 2014)
- **Locally and adaptively refined meshes** (Angelidis et al, *J. Comp. Physics* 2015).

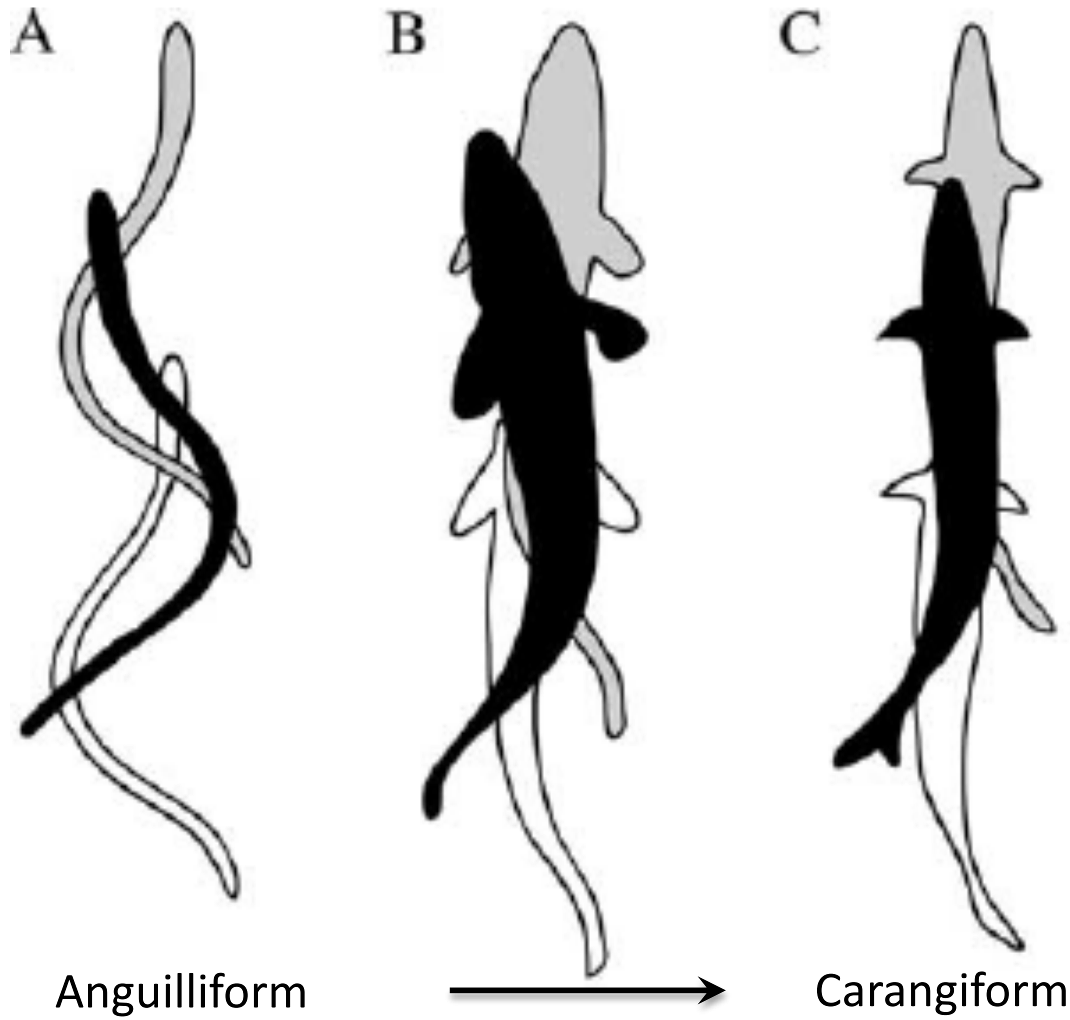




http://safl-cfd-lab.github.io/VFS-Wind/

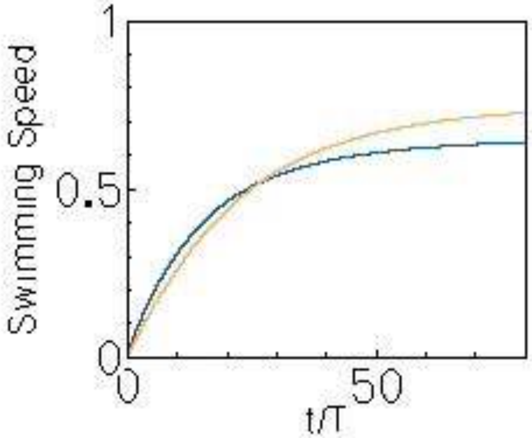
Hydrodynamics and Fish Evolution

Borazjani & Sotiropoulos, J. Exp. Biology, 2009, 2012

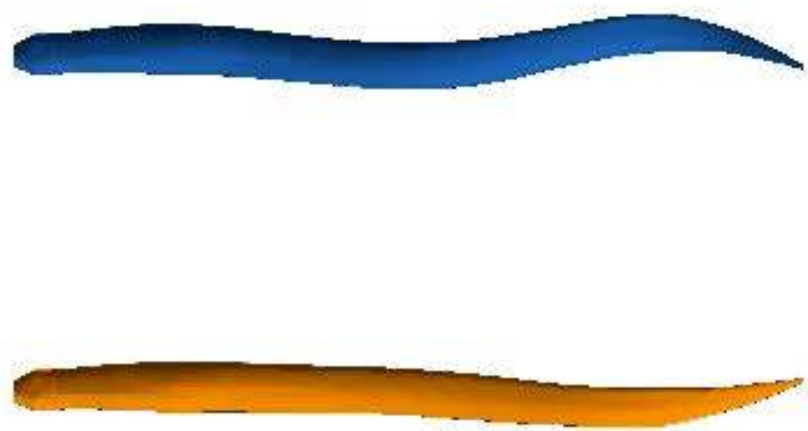


What if a Mackerel could swim like an Eel or an Eel swim like a Mackerel?

Borazjani & Sotiropoulos, J. Exp. Biology, 2009, 2012



Lamprey body
Re=∝ (Inviscid) St~0.3
Anguilliform Kinematics
Carangiform Kinematics

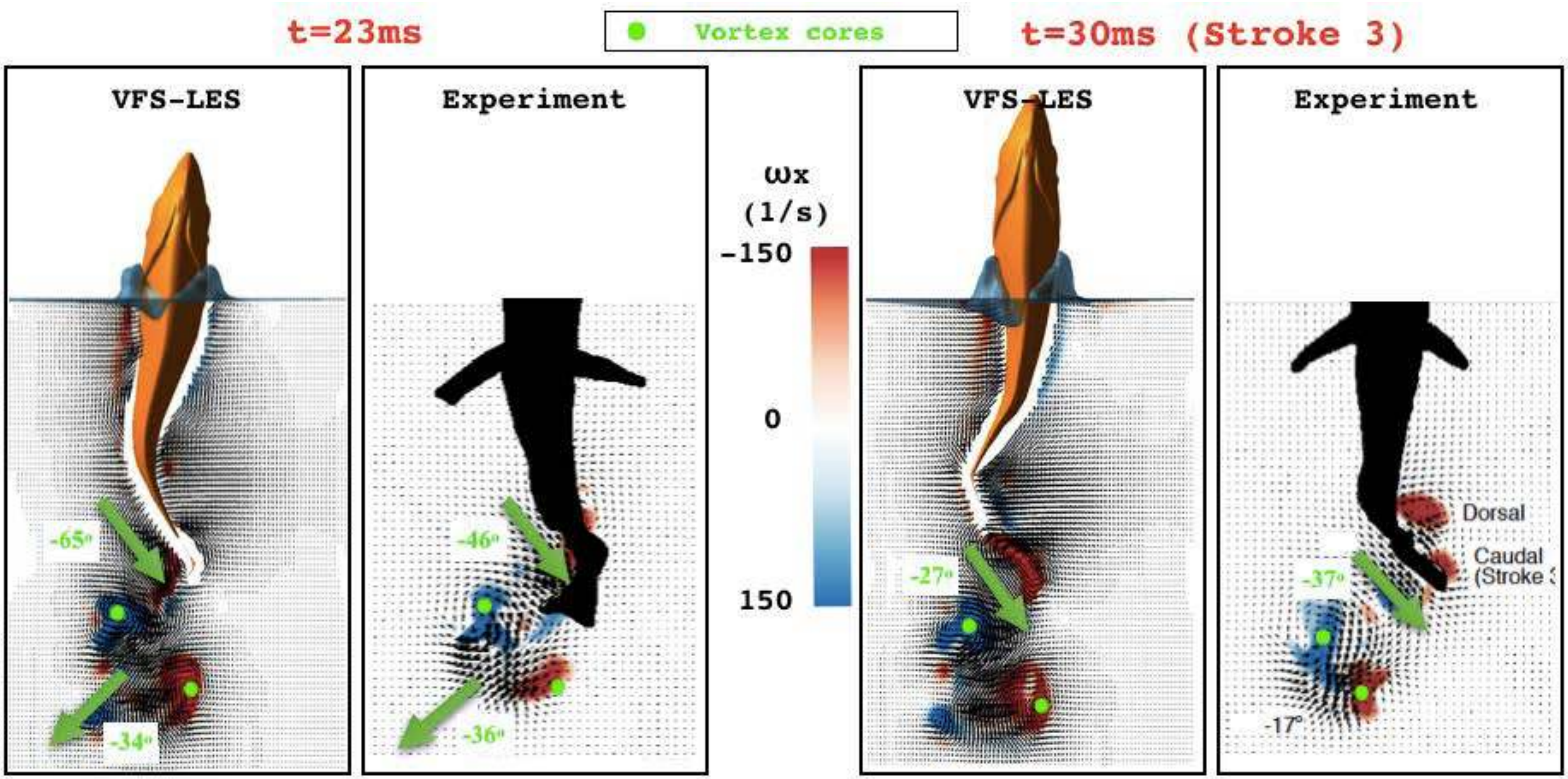


The camera is fixed on the slower (top) lamrpey.
The distance is scaled by half for better visualization.

Hydrodynamics of Archer fish jumping out of water

With Alex Techet (MIT) & Leah Meldenson (Harvey Mud)

Comparison of simulations with measurements



Comparison of the propulsive jets and the instantaneous out-of-plane vorticity contours between LES and PIV measurements. PIV time series correspond to 1 body length jump and LES calculations to 2.3 body length jump of the same specimen.

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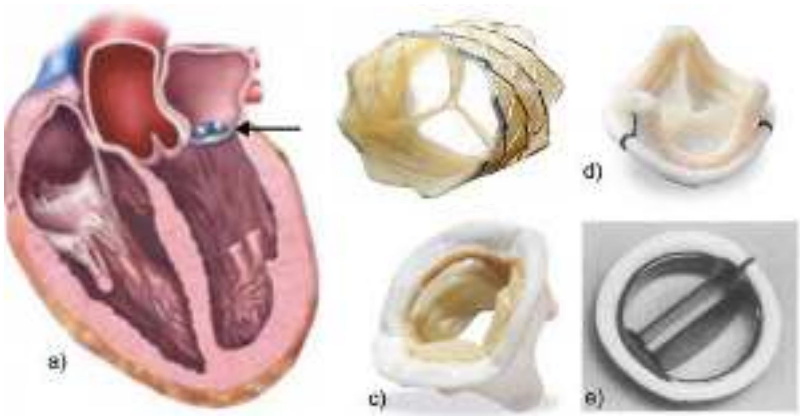
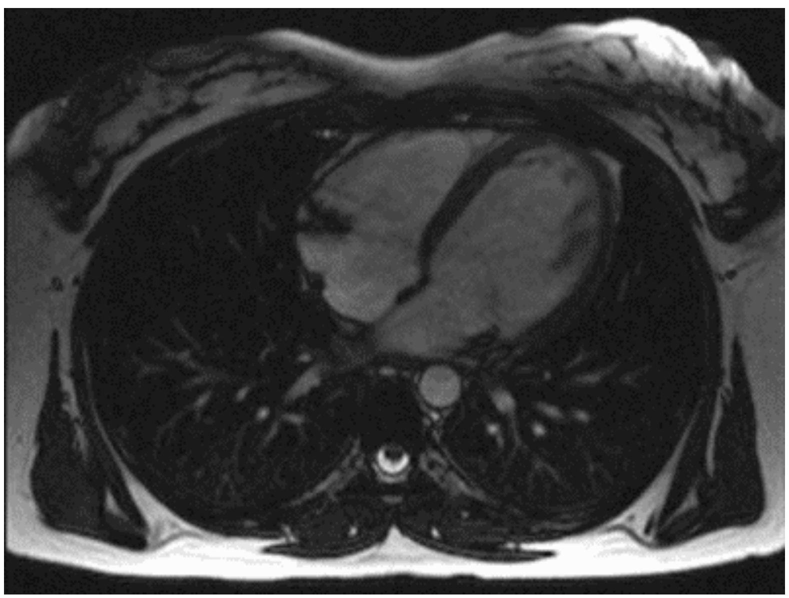
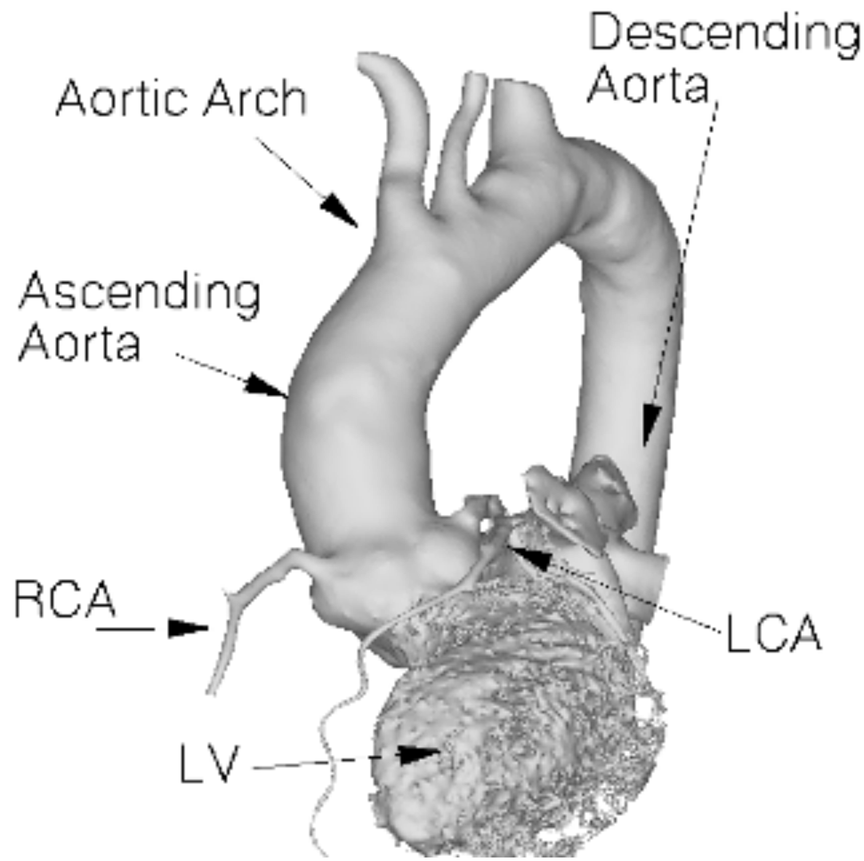
Water exit dynamics of jumping archer fish

With Alex Techet (MIT) &
Leah Meldenson (Harvey Mud)

Image-guided patient-specific simulations of aortic valves

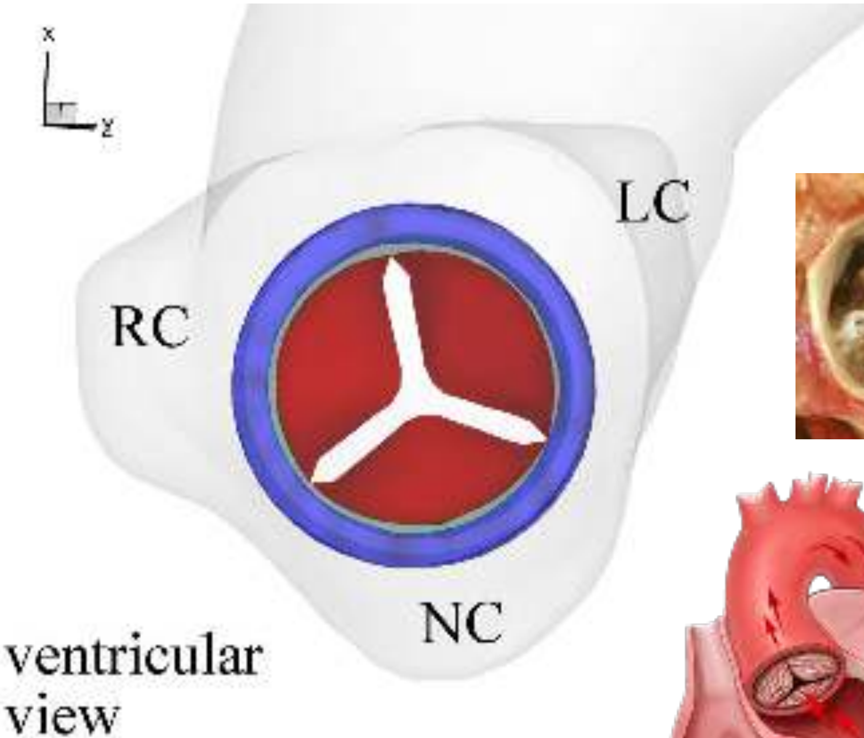


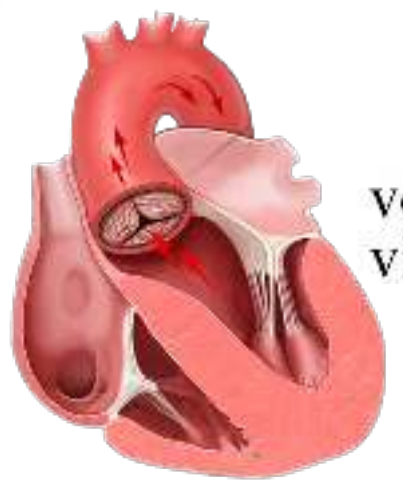


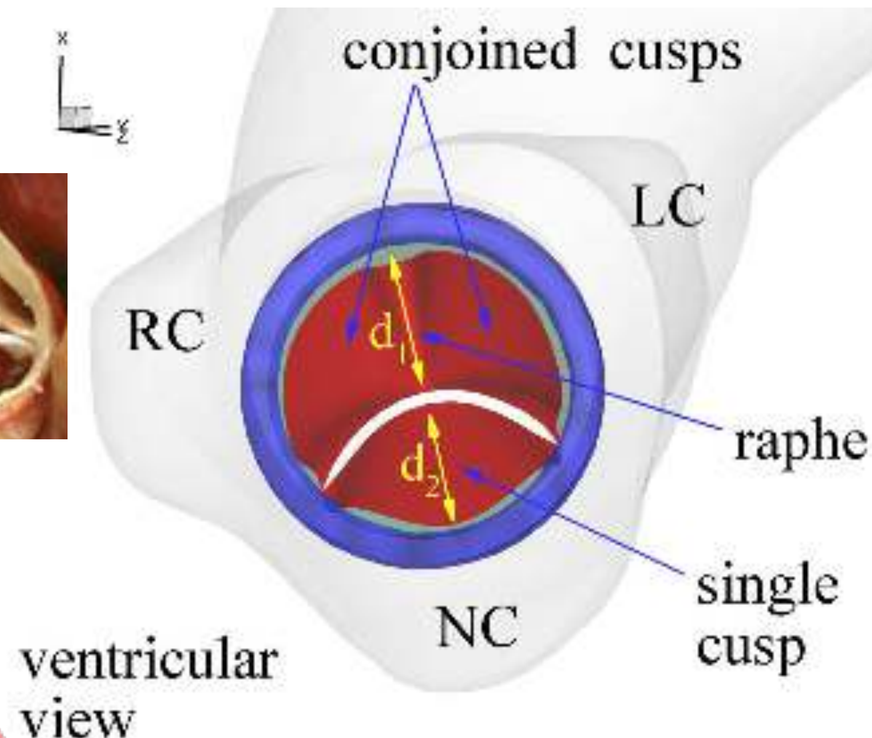


From MRI to high-resolution computational modeling

The hemodynamics of aortic valves: Tricuspid vs. bicuspid valves







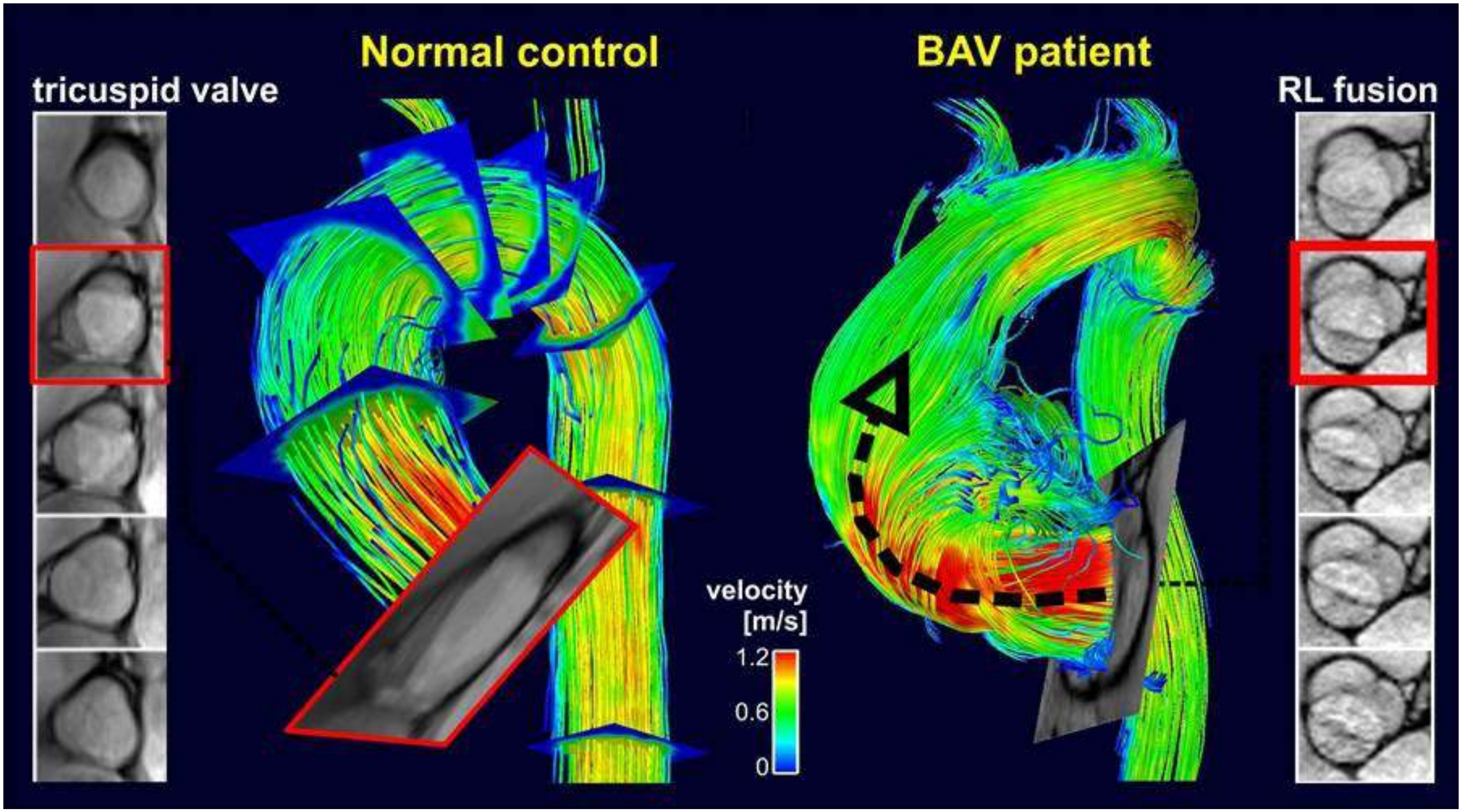
$$\varepsilon = d_1/d_2 = 1.25$$

Bicuspic aortic valve (BAV) occurs in ~1-2% of the population

A. Gilmanov, & F. Sotiropoulos, "Comparative hemodynamics in an aorta with bicuspid and trileaflet valves," Theor. Comput. Fluid Dyn. 2016

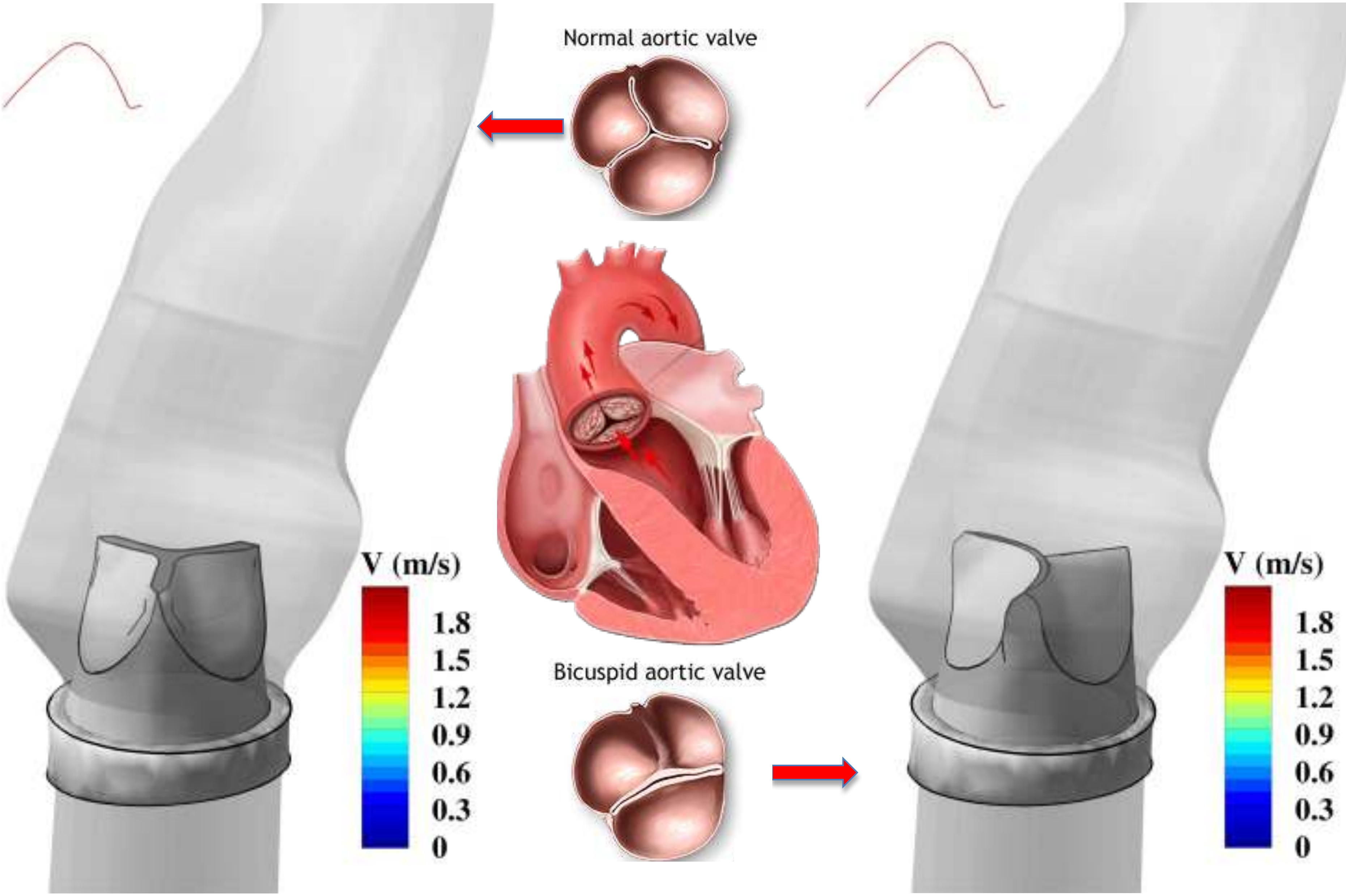
BAV patients show increased prevalence of aortopathies

Genetics or hemodynamics?

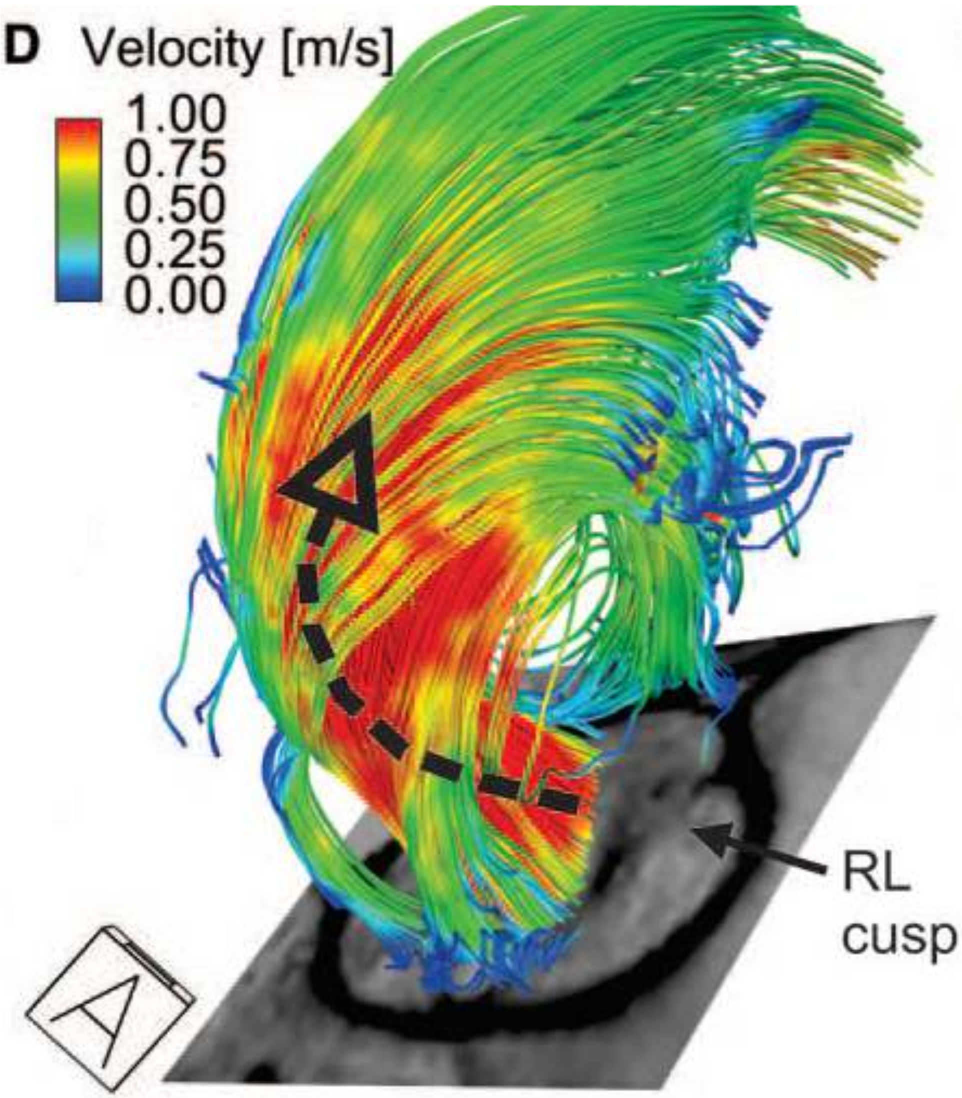


Bissell, et al .
Circ. Cardiovasc. Imaging 2013

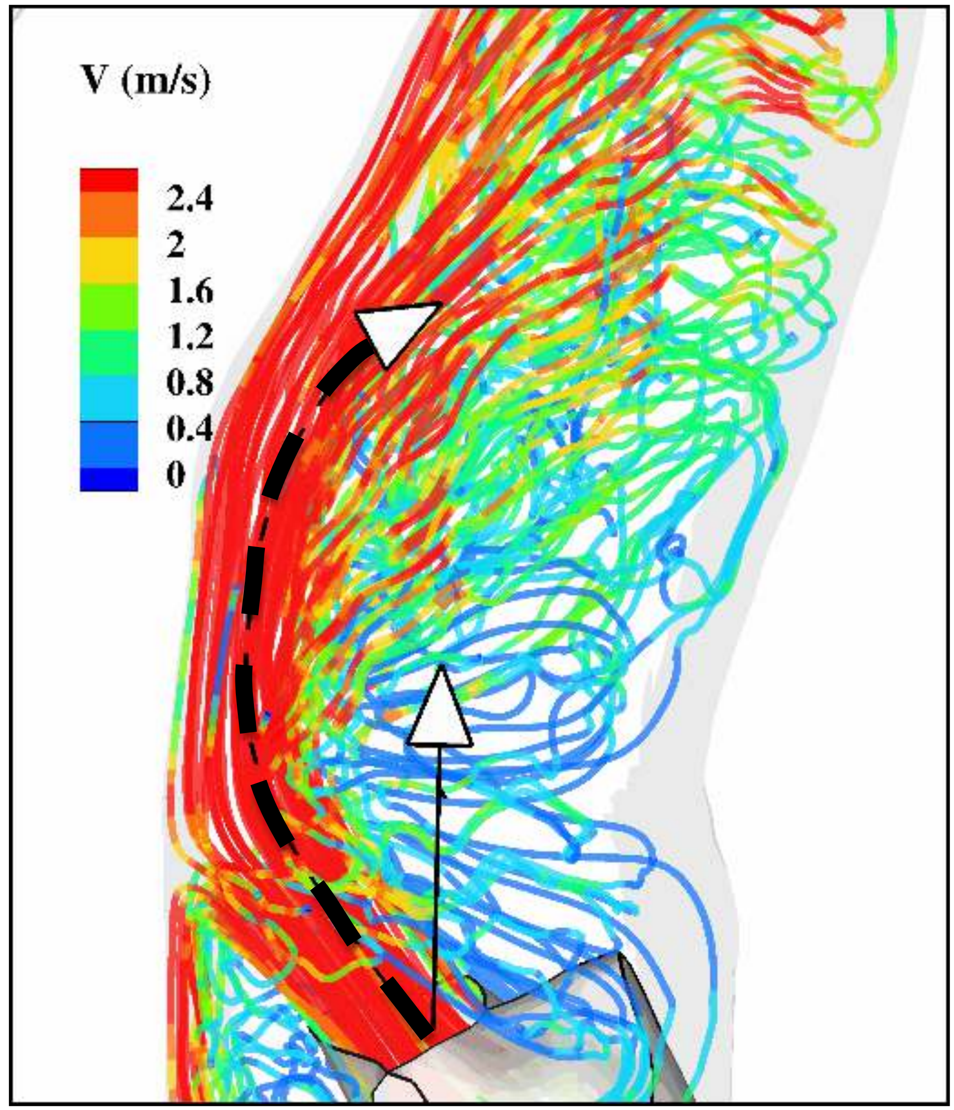
Instantaneous streamlines



Comparison with 4D MRI
Bicuspid aortic valve



Bissell, et al .
Circ. Cardiovasc. Imaging 2013



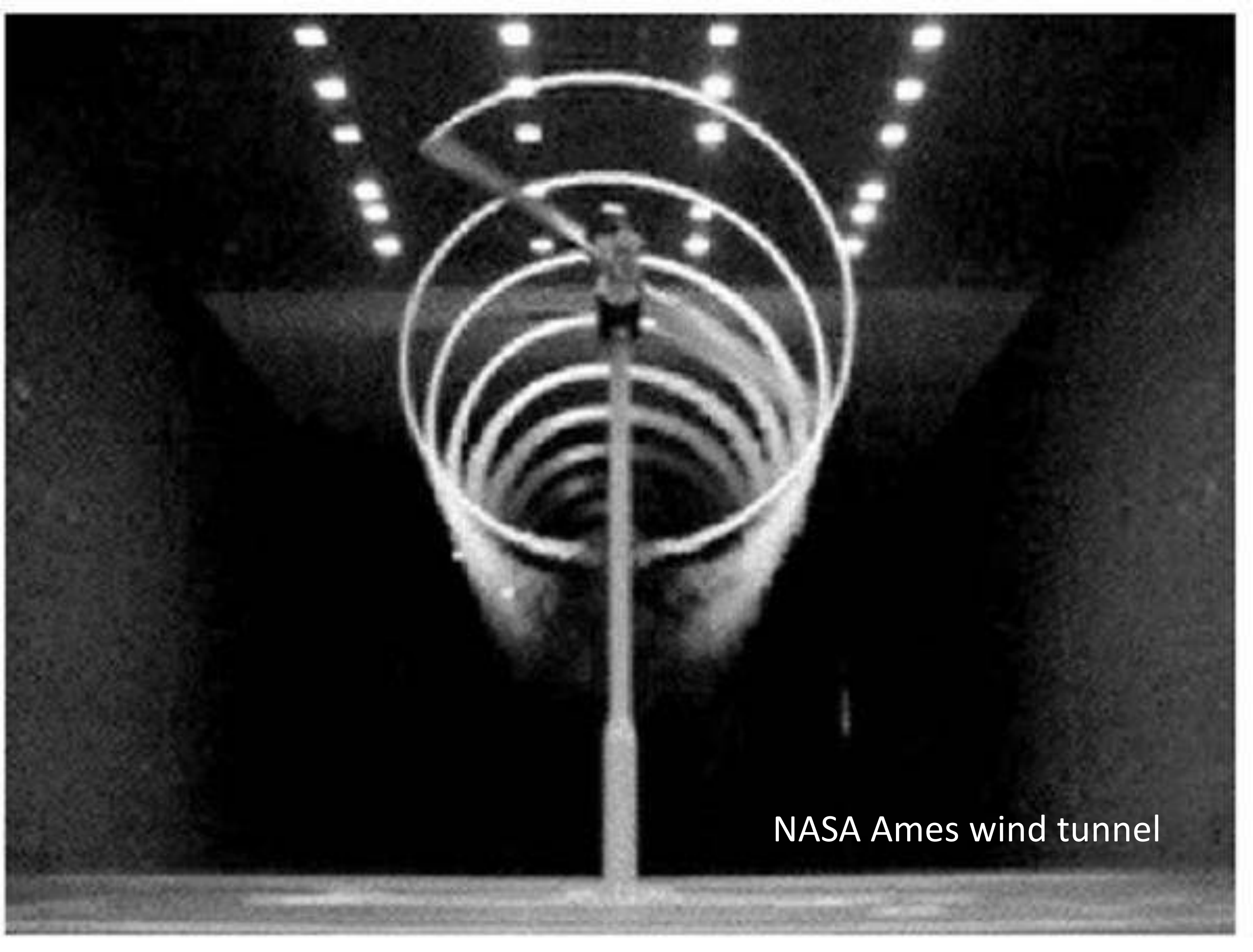
Gilmanov & Sotiropoulos
Theo. & Comp. Fluid Dyn. 2015

Simulation-based design and optimization of wind farms

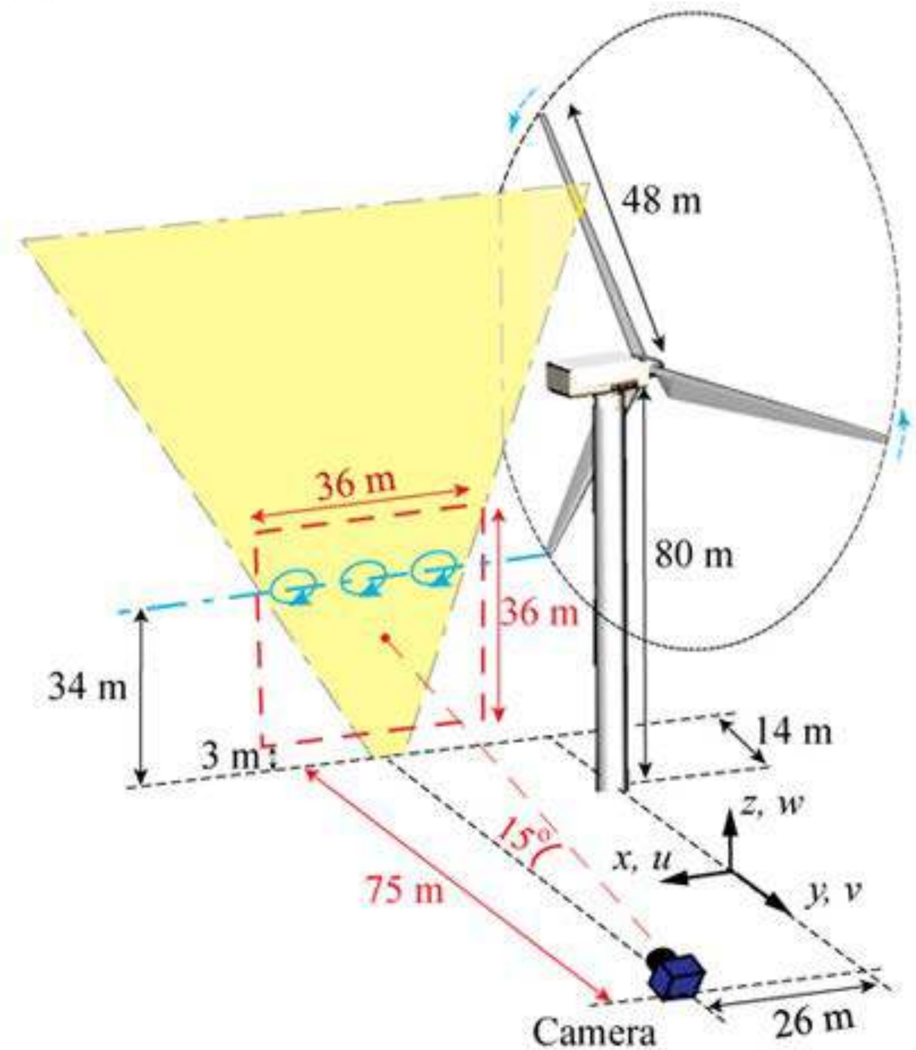
"The largest remaining opportunities to ***reduce the cost of energy*** *will come from substantial gains in* ***understanding complex wind plant aerodynamics****."* EERE DOE.

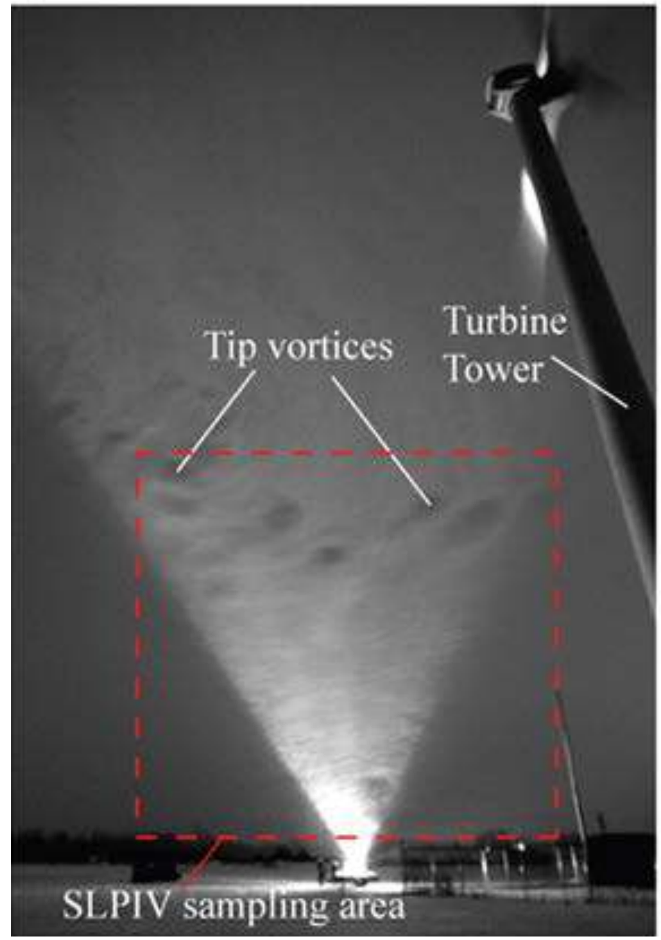
The Horns Rev Offshore wind farm
Denmark, North Sea

Tip vortices in the wind tunnel



A Utility-Scale (2.5MW) “Wind Tunnel”

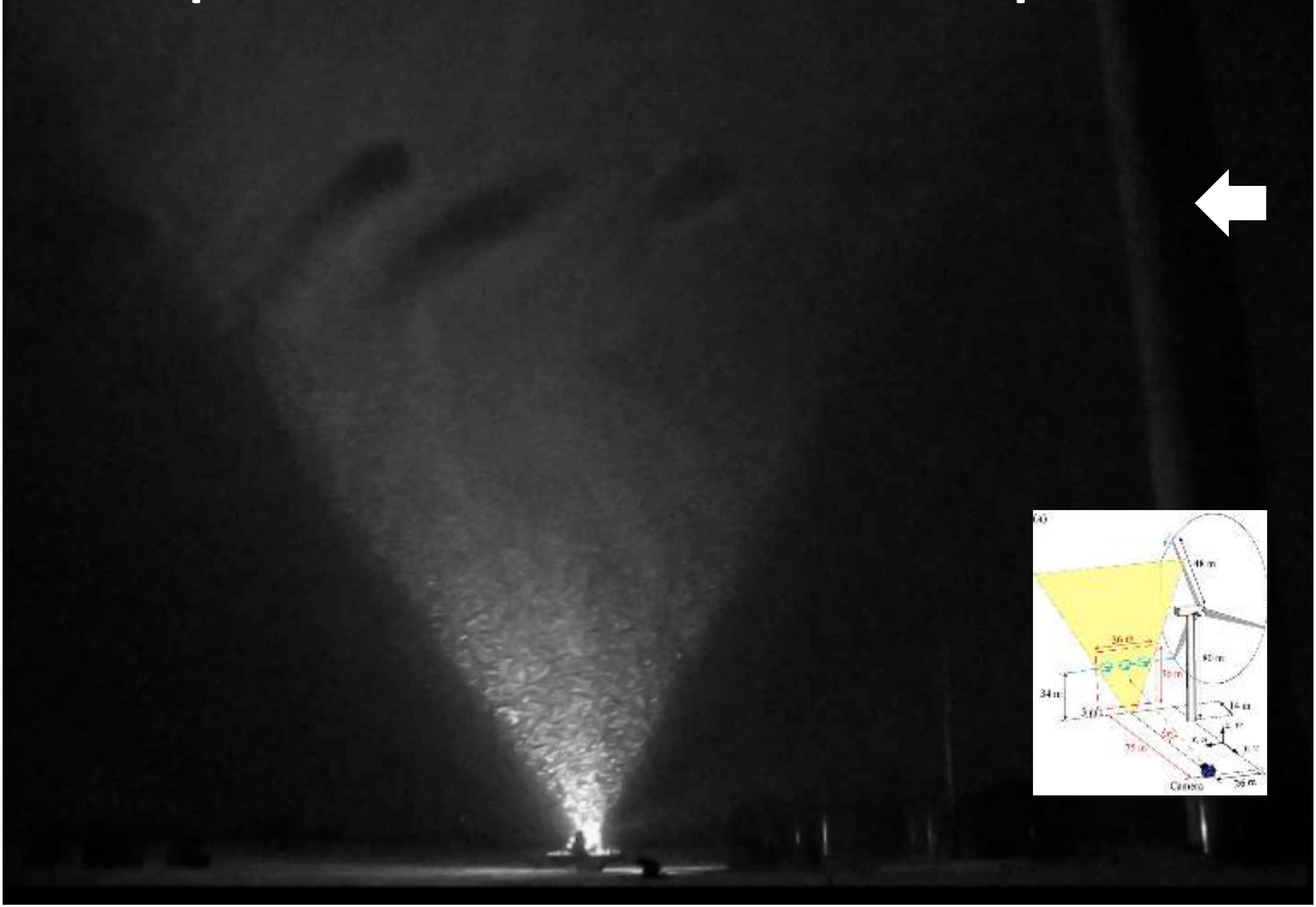




Super Large Scale PIV (SLPIV) using natural snow as tracer implemented at the University of Minnesota 2.5MW EOLOS turbine (Rosemount, MN)

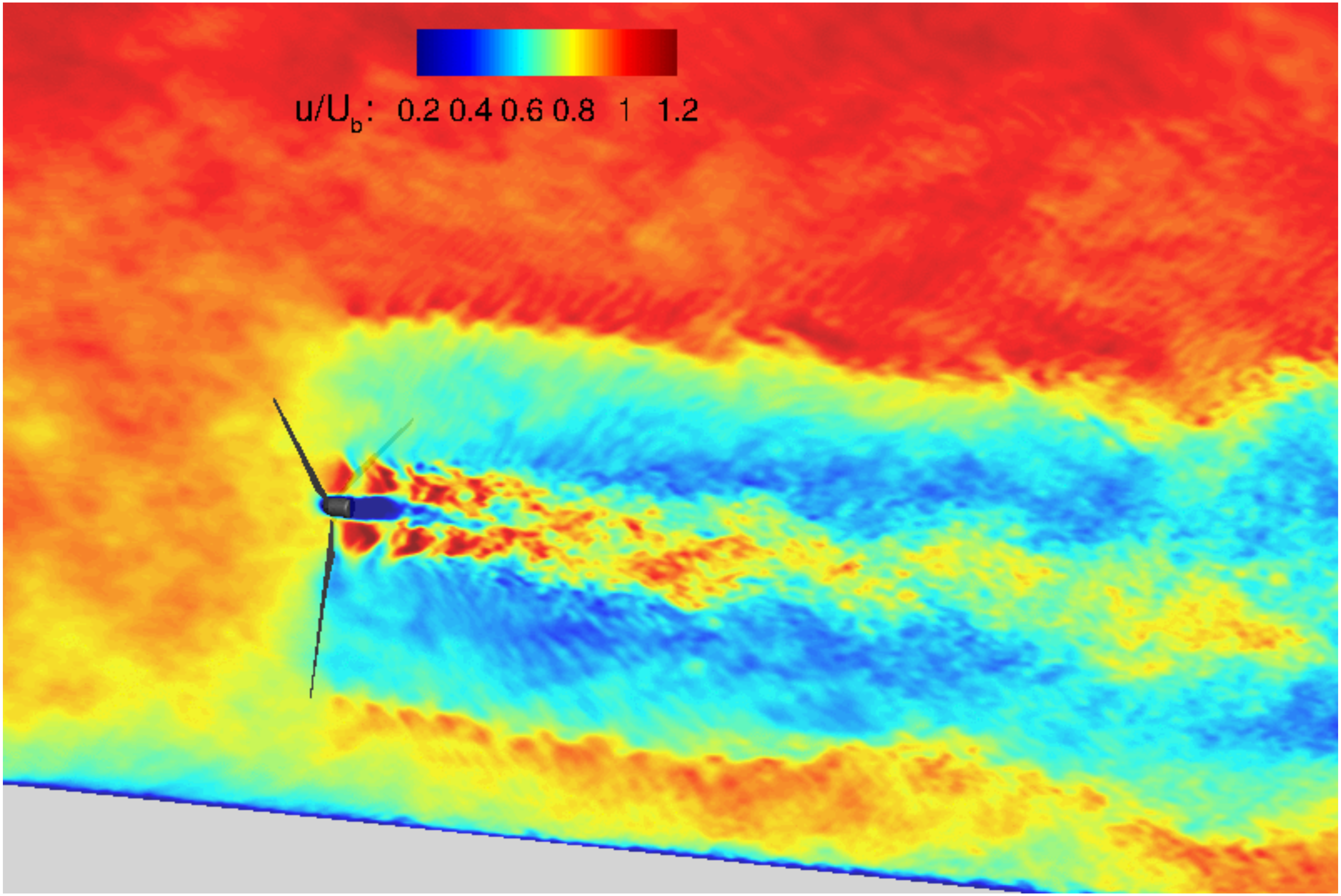
Hong et al., Nature Comm., 2014.

Complex flows in the near wake: Tip vortices



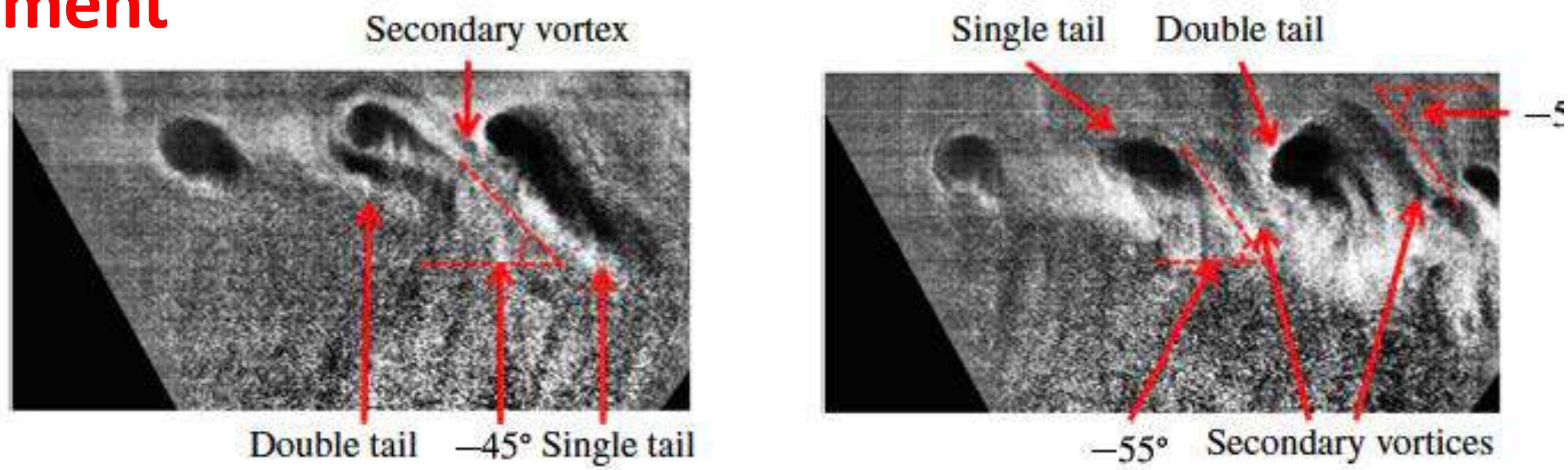
Numerical simulation

Tip speed ratio = 9; Inflow turbulence; Stably stratified atmosphere

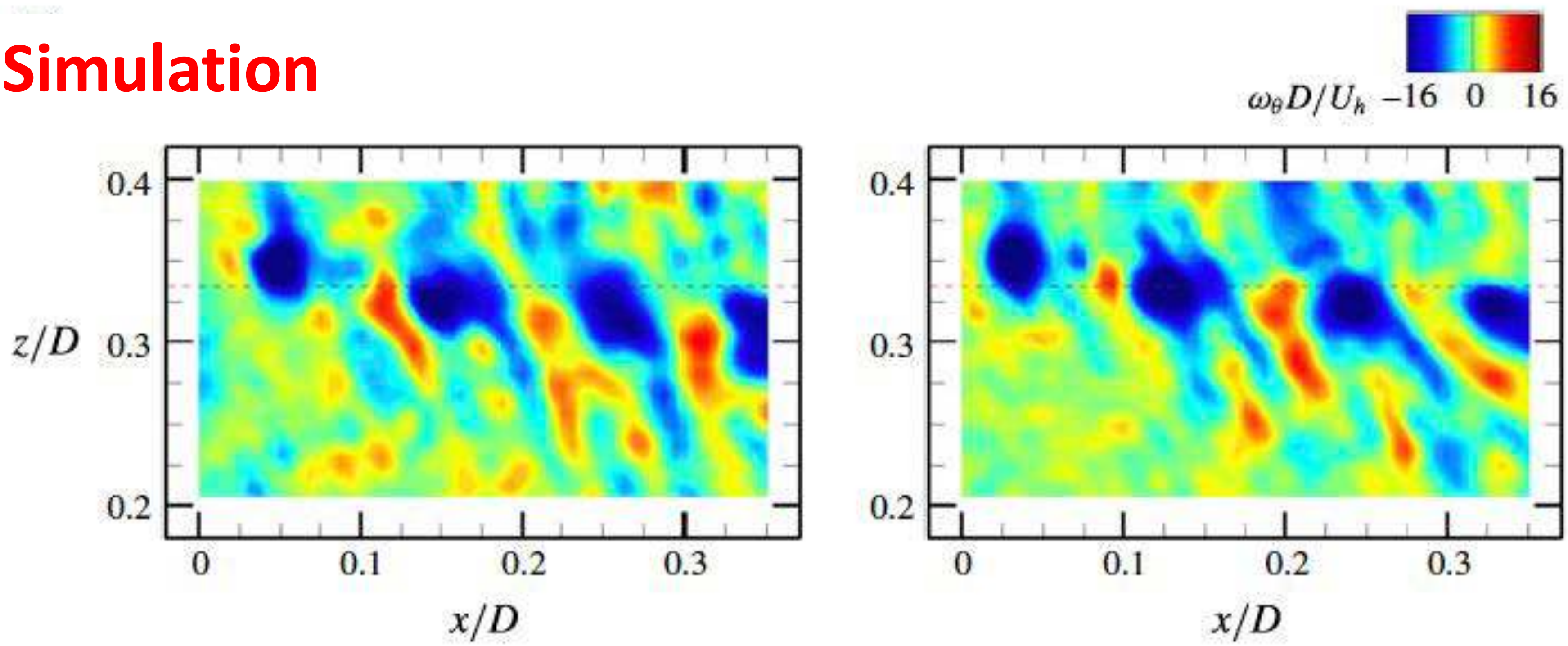


Vorticity magnitude as surrogate for snow voids

Experiment

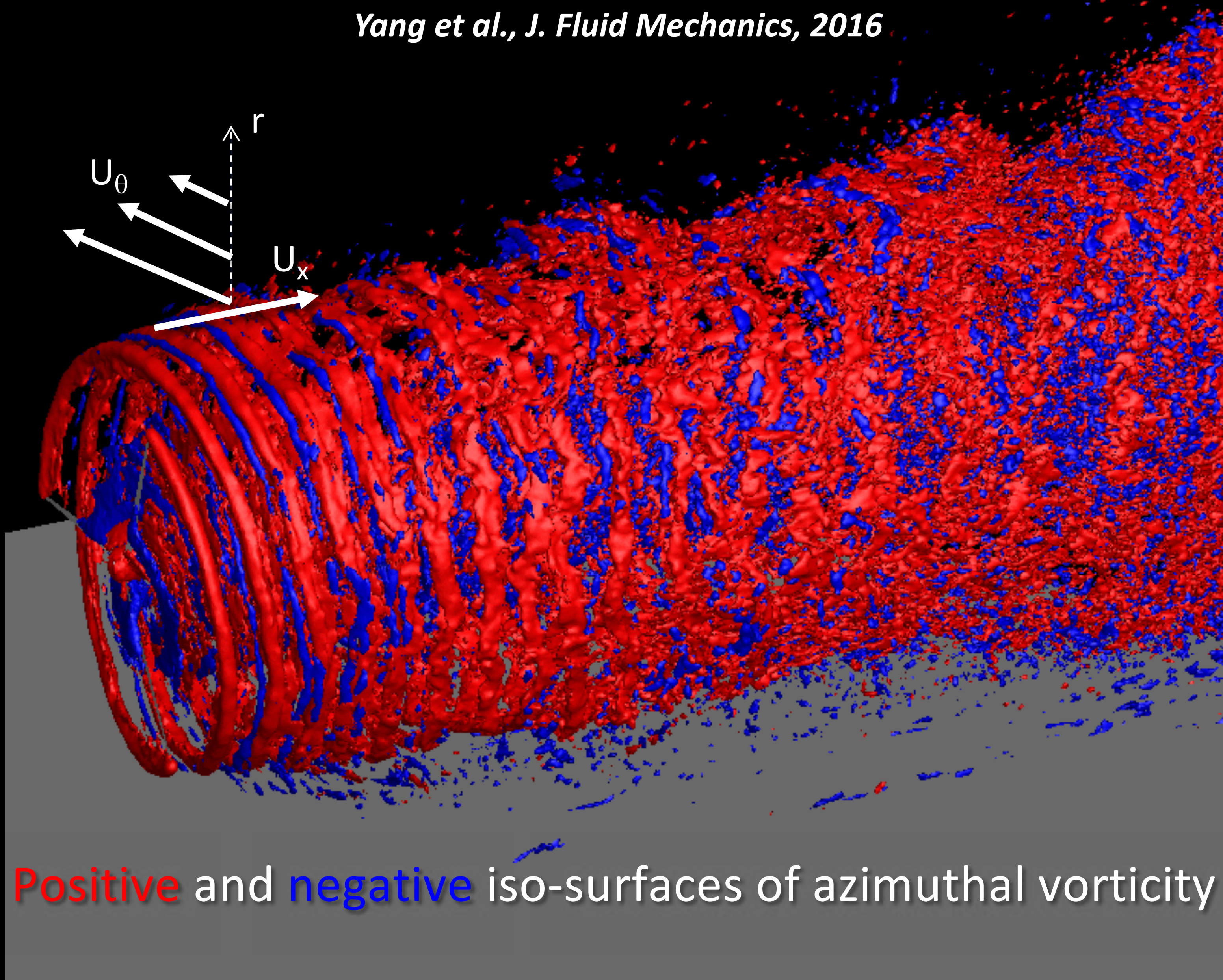


Simulation

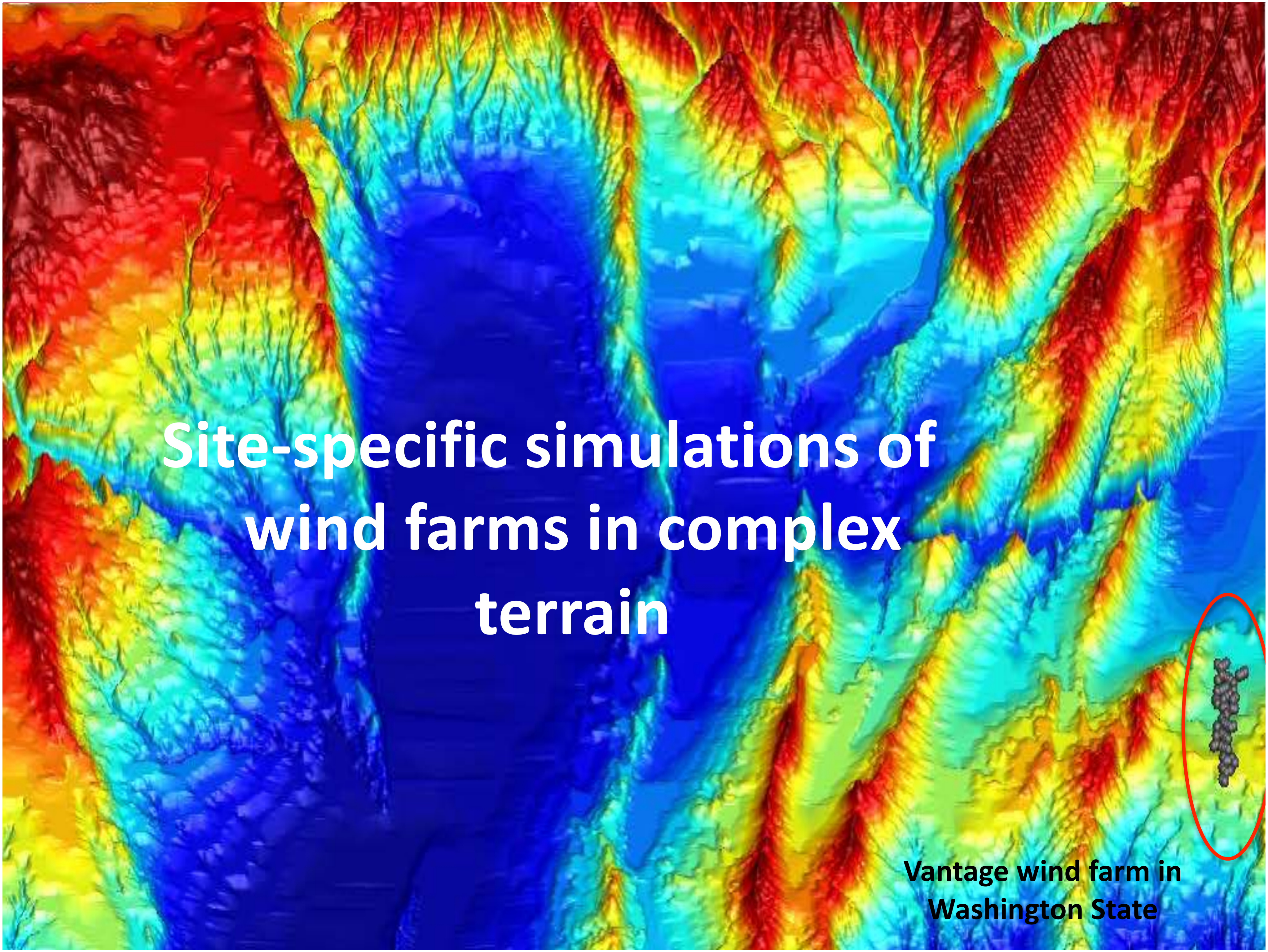


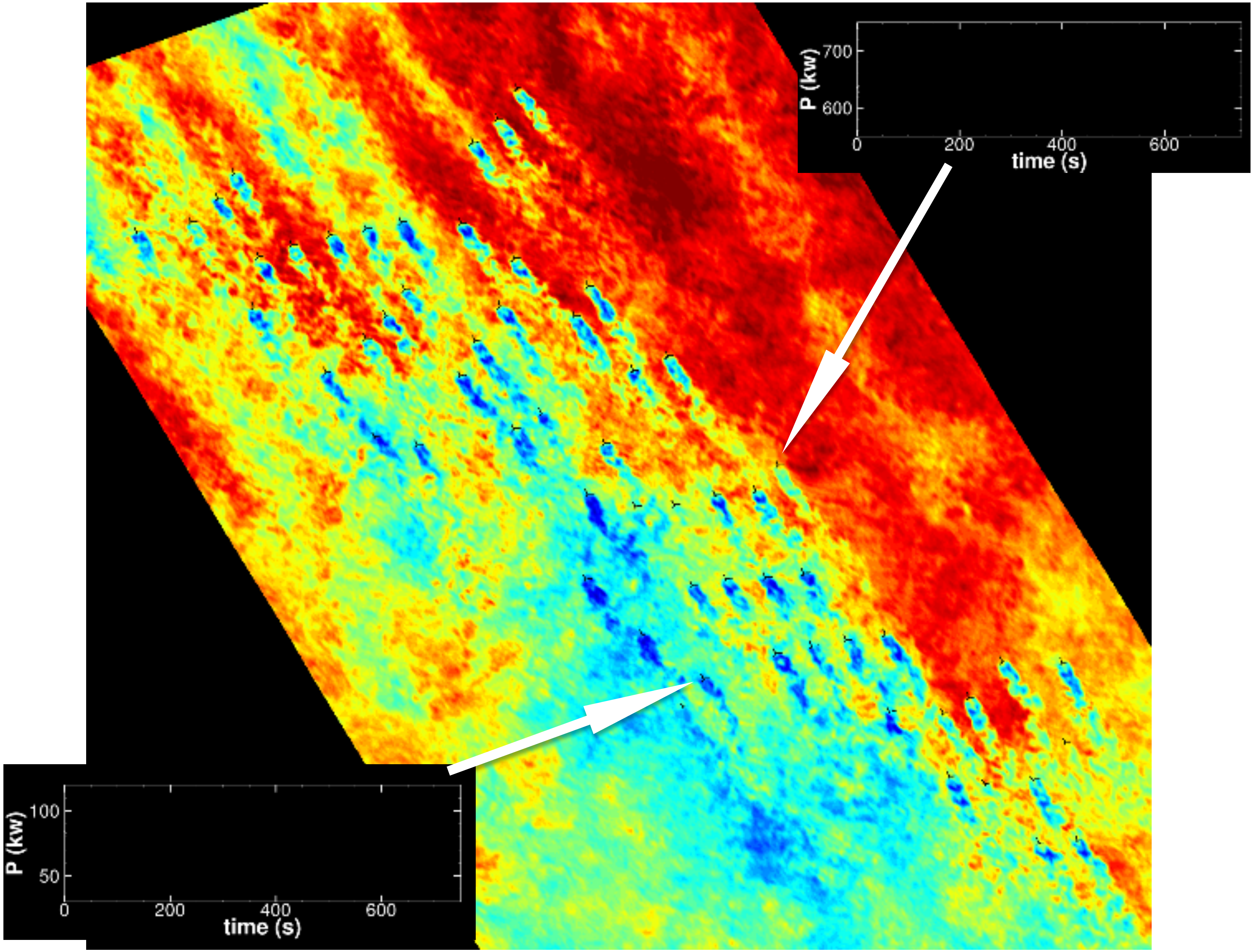
Coherent dynamics in the rotor tip shear layer of utility-scale wind turbines

Yang et al., J. Fluid Mechanics, 2016



Wind farms in complex terrain

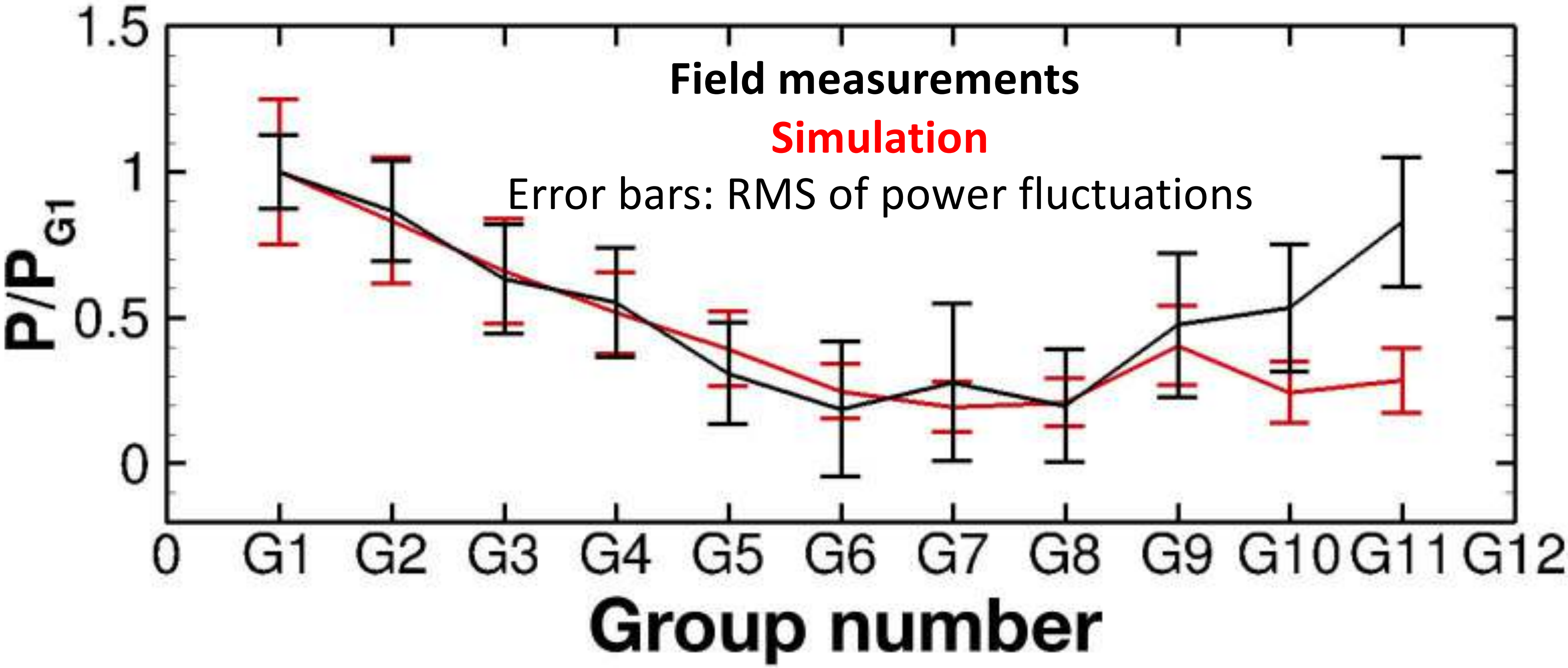

Site-specific simulations of wind farms in complex terrain
Vantage wind farm in Washington State



P (kw)
700
600
0
200
400
600
time (s)
P (kw)
100
50
0
200
400
600
time (s)

LES of a utility-scale wind farm in complex terrain

Yang, Pakula & Sotiropoulos, *Applied Energy, 2018*

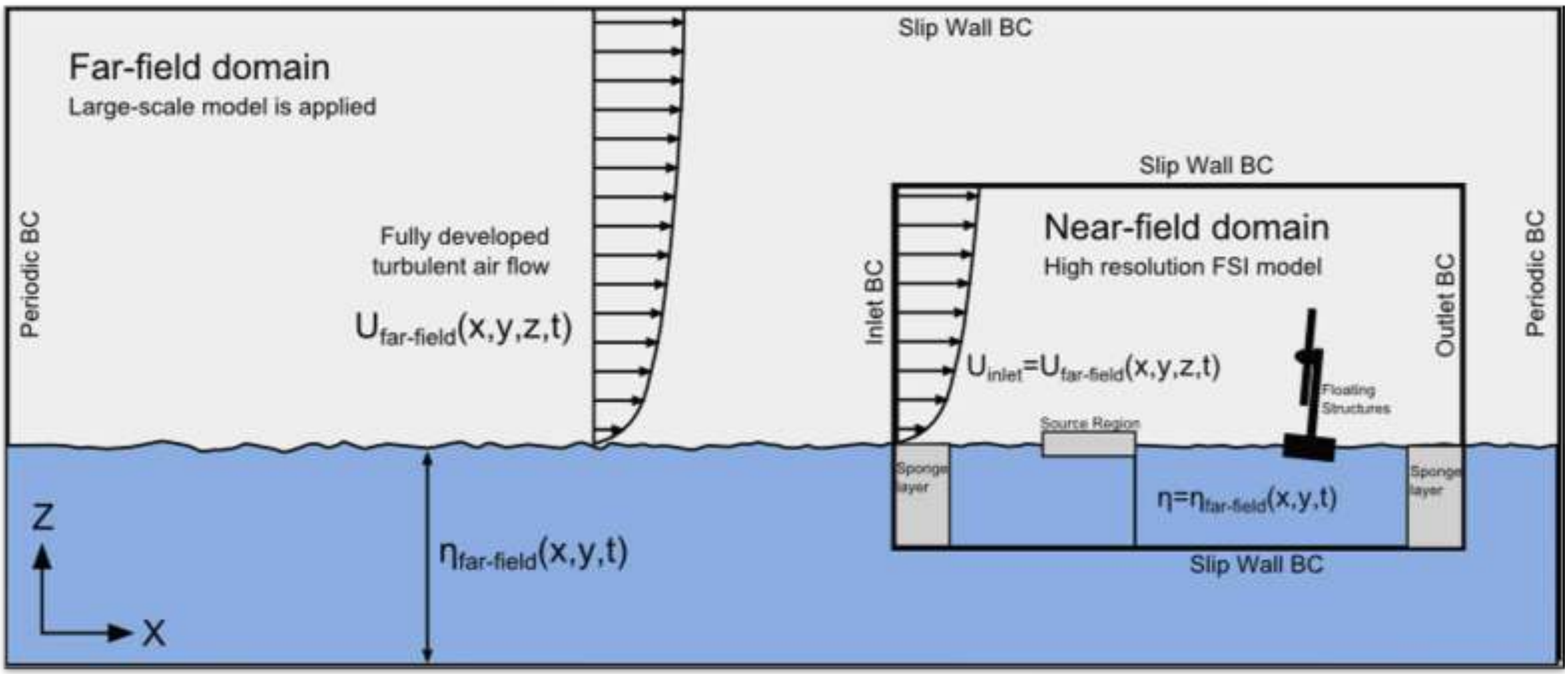


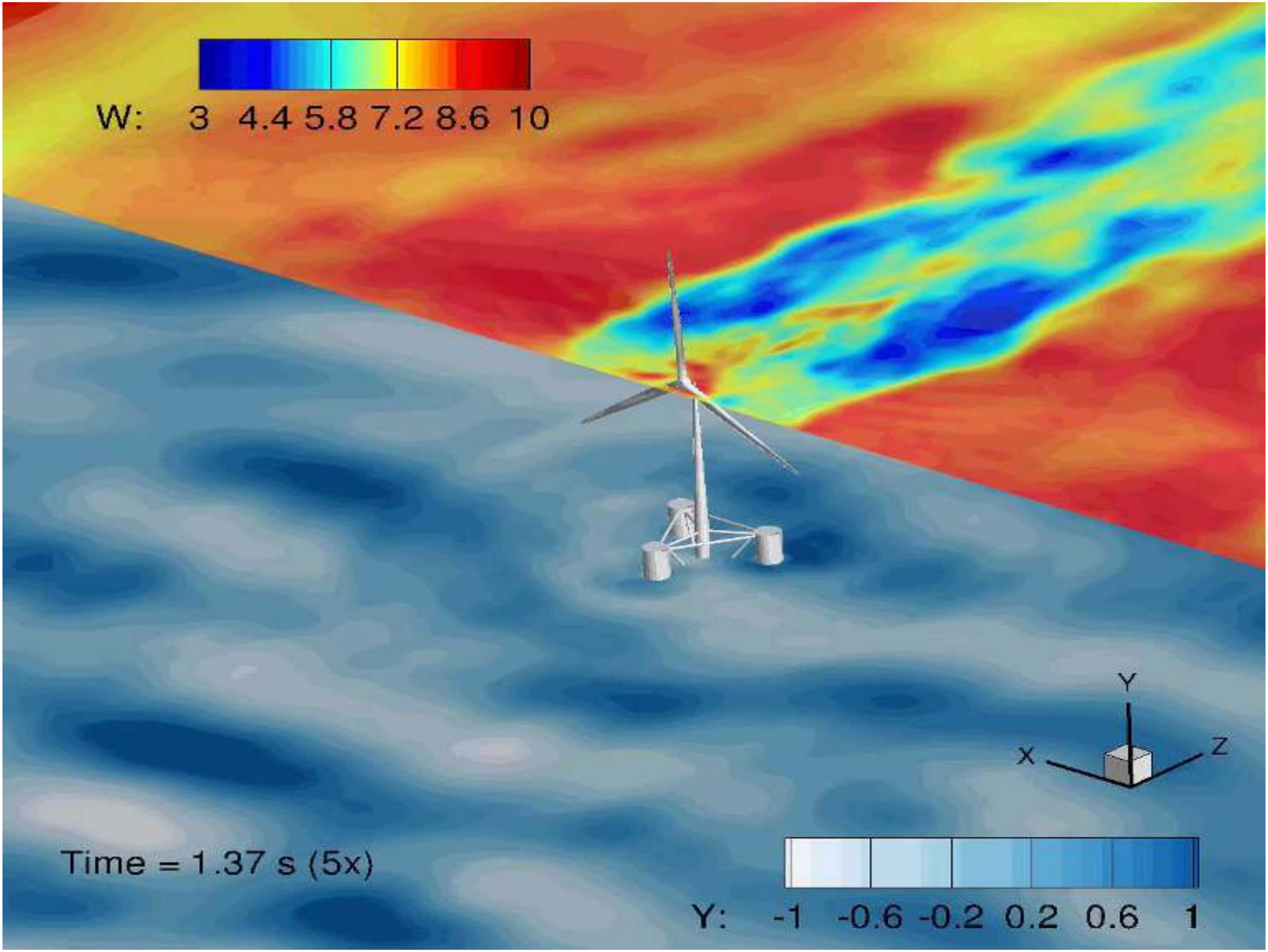
Measured vs computed mean and RMS fluctuations of power

P: averaged power of each group; P_{G1}: averaged power of G1 group

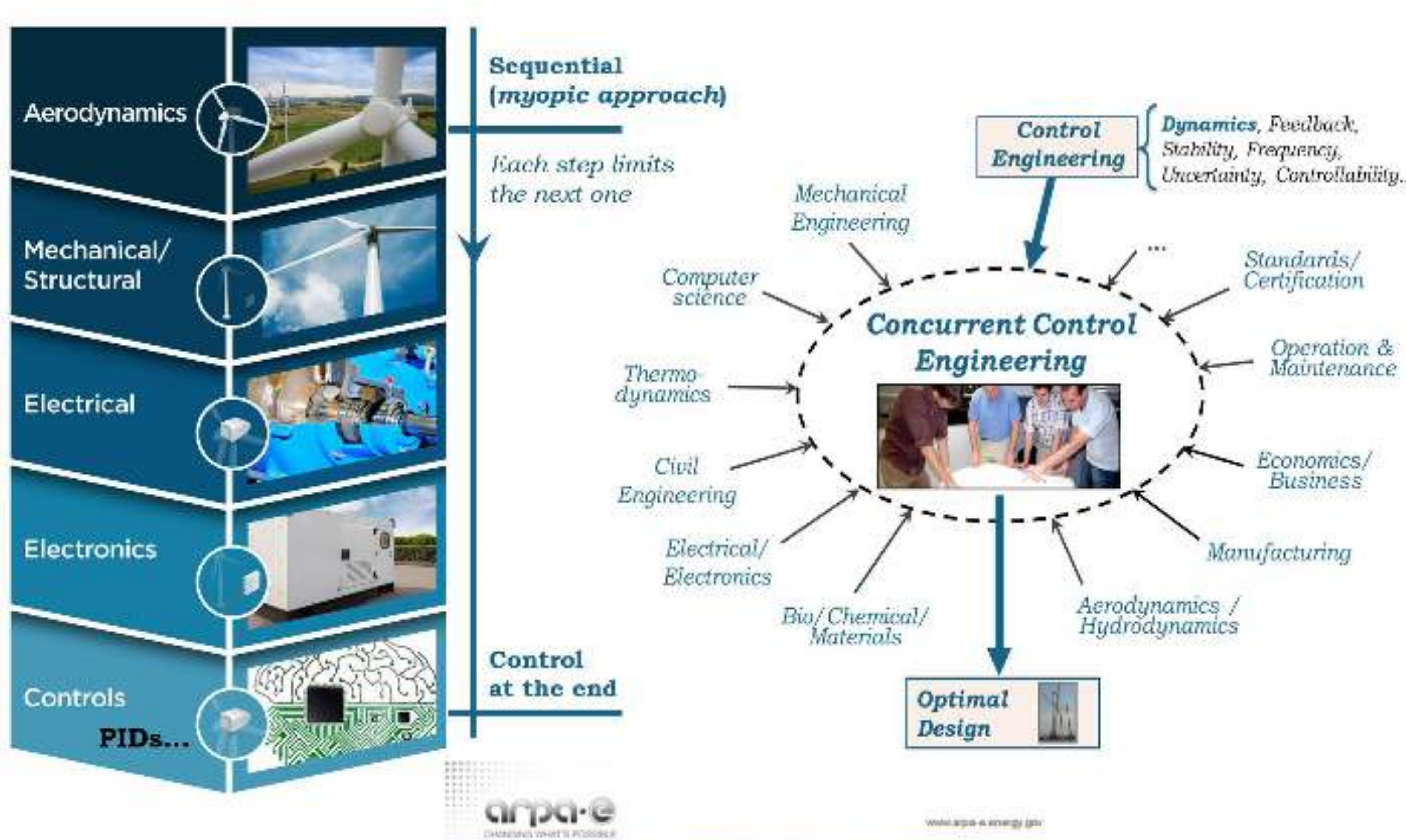
Fluid-structure interaction simulation of floating structures interacting with complex, large-scale ocean waves and atmospheric turbulence

Calderer et al., J. Comp. Physics, 2018




W: 3 4.4 5.8 7.2 8.6 10
Y
X
Z
Time = 1.37 s (5x)
Y: -1 -0.6 -0.2 0.2 0.6 1

Control co-design of offshore wind farms



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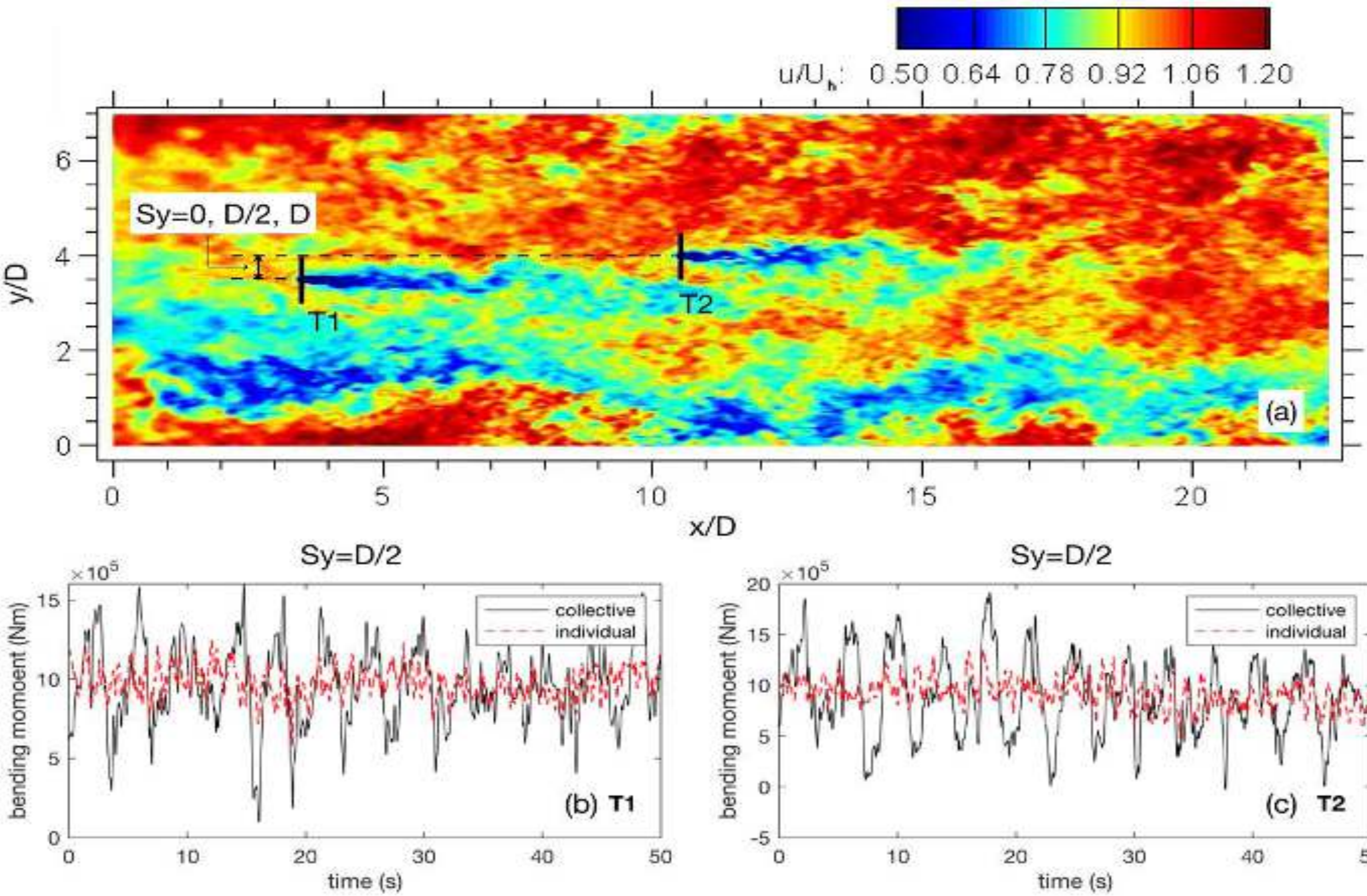
Individual vs collective pitch control

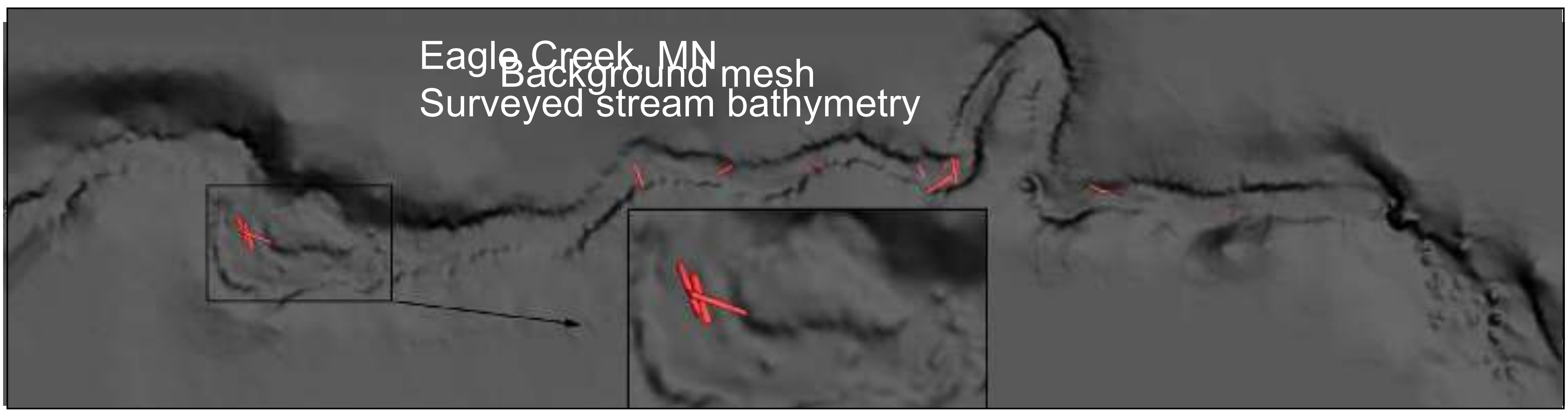
Individual vs collective blade pitch control



Individual Pitch Control can reduce blade bending loads

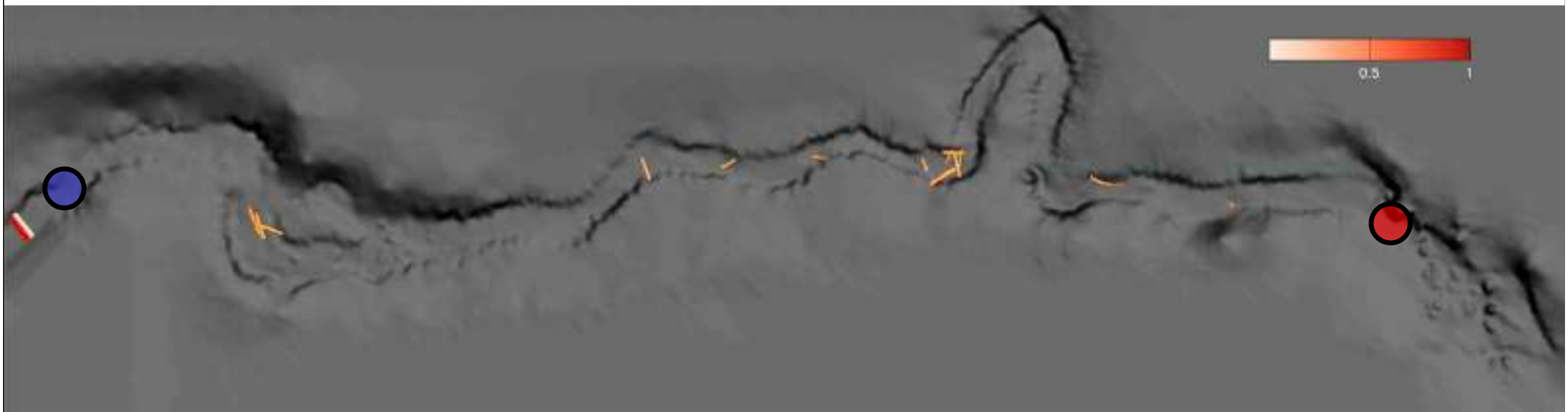
Site specific simulations of turbulence in waterways

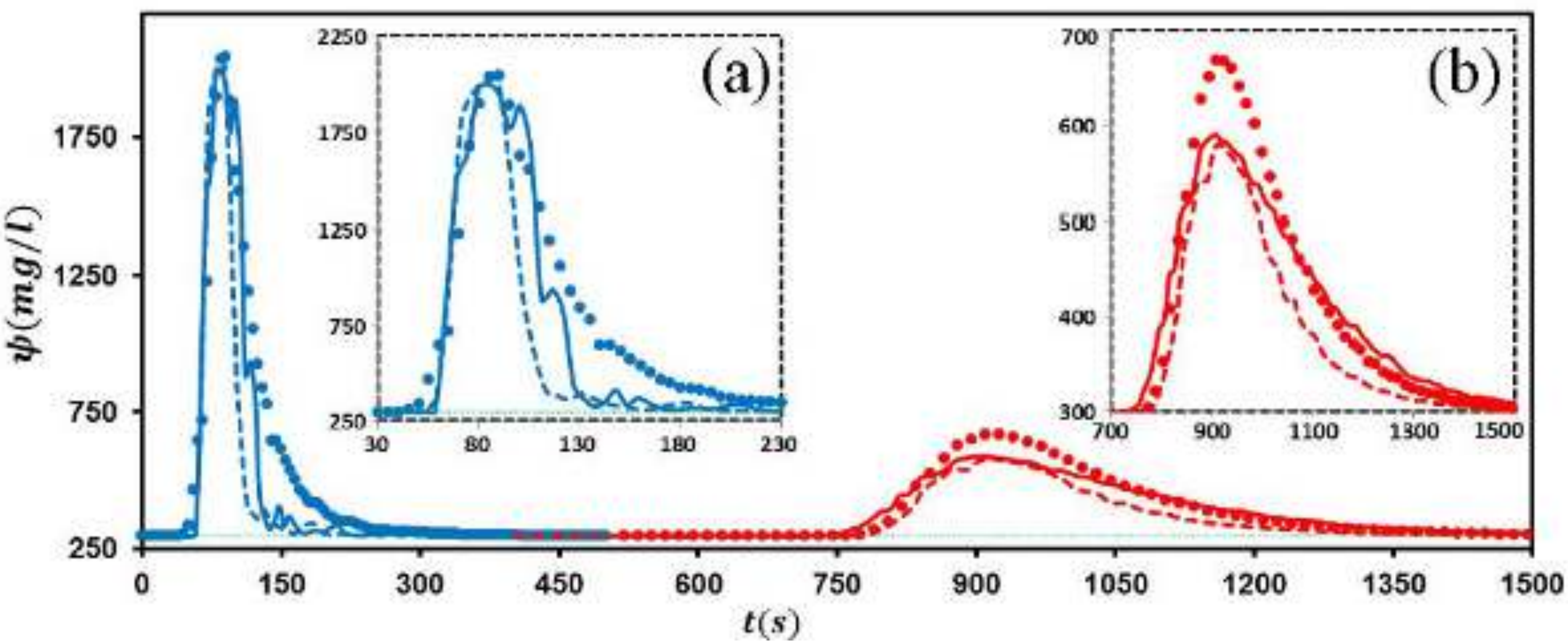
Khosronejad et al., J. Geophysical Research 2016



Data-driven site-specific simulations of turbulence and solute transport in waterways

Large-eddy simulation of solute transport in Eagle Creek, MN



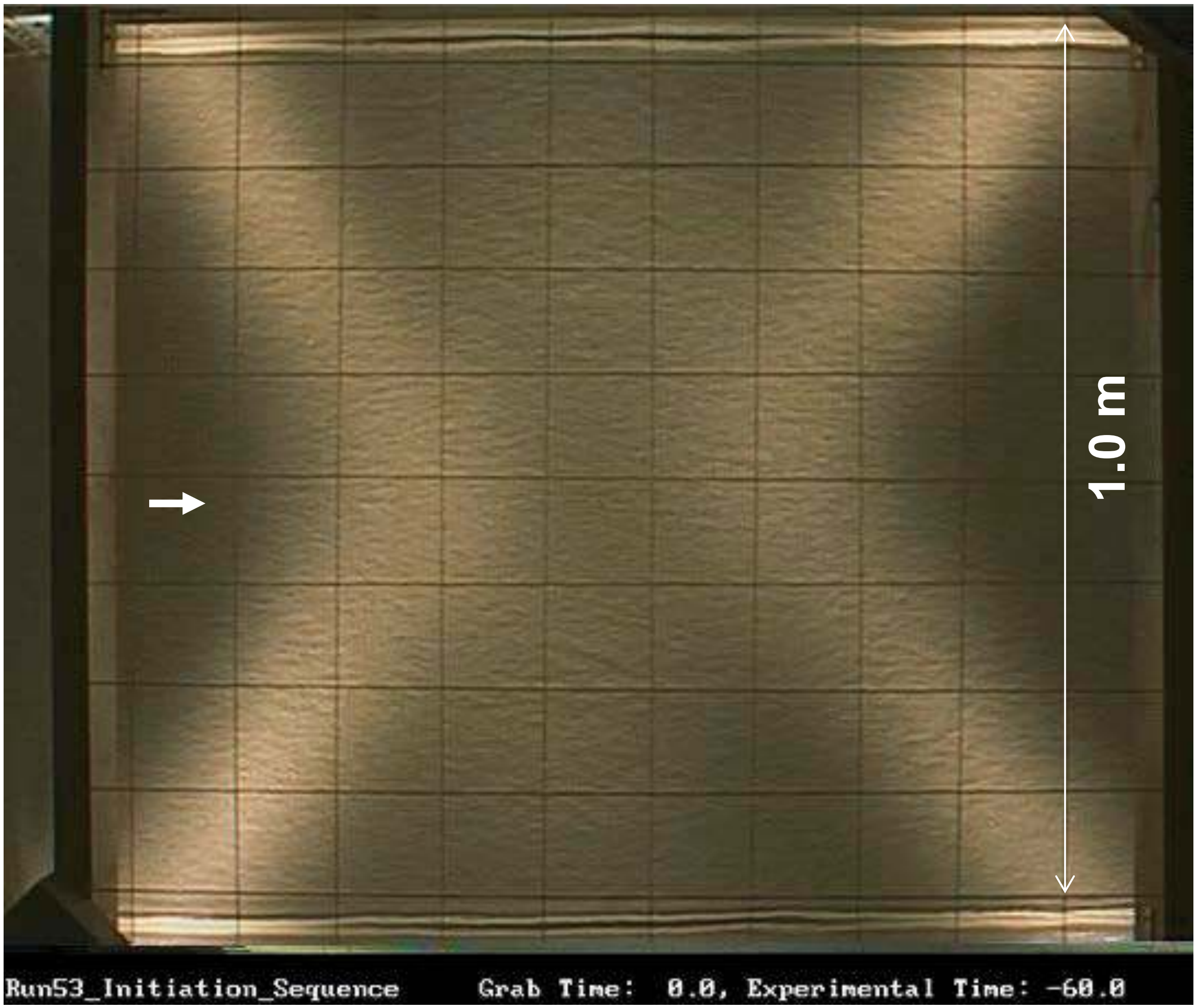


Sand waves in waterways

- How do they originate?
- What is their impact on infrastructure?

Sand waves in a laboratory flume

Venditti, Church & Bennett, J. of Geophysical Research, 2005



LES of turbulent flow over a mobile sand bed

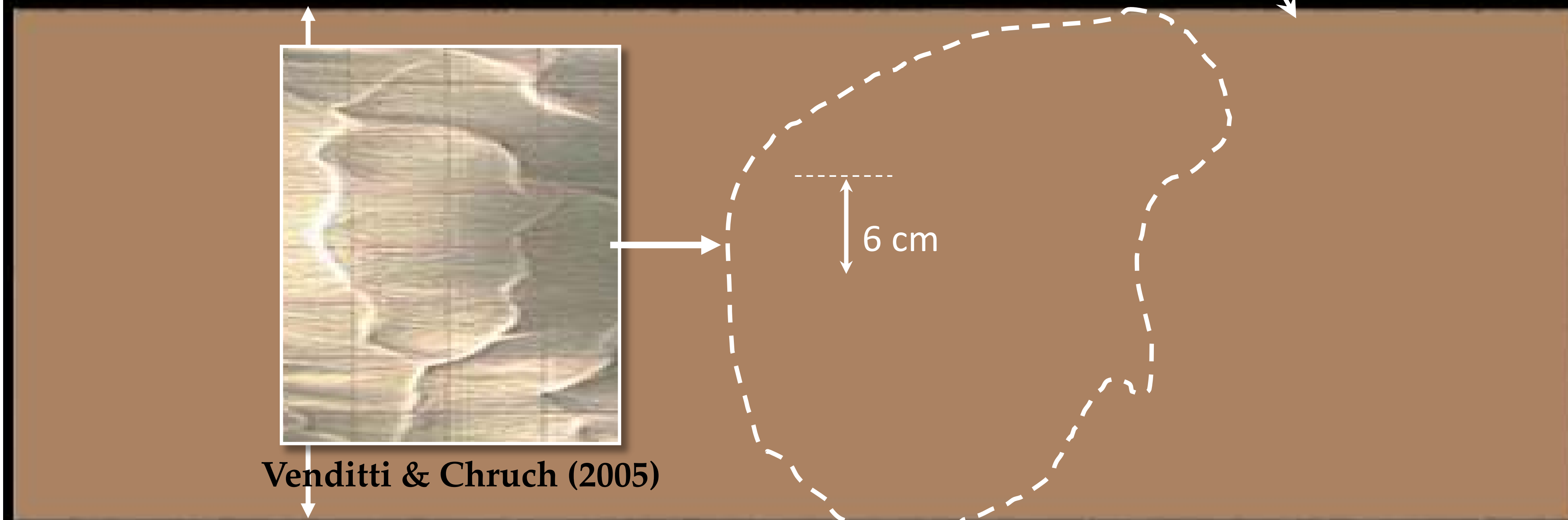
Khosronejad & Sotiropoulos, J. Fluid Mech. 2014

Transition to 3D pattern

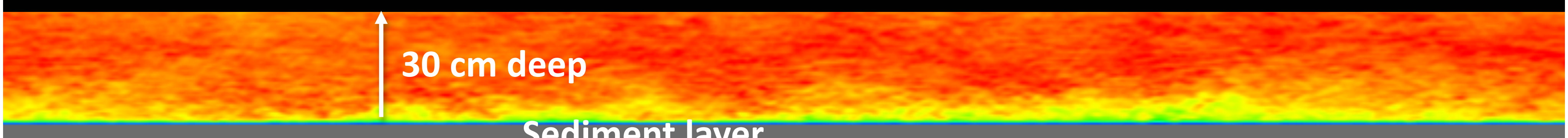
3D pattern

Sand wave initiation

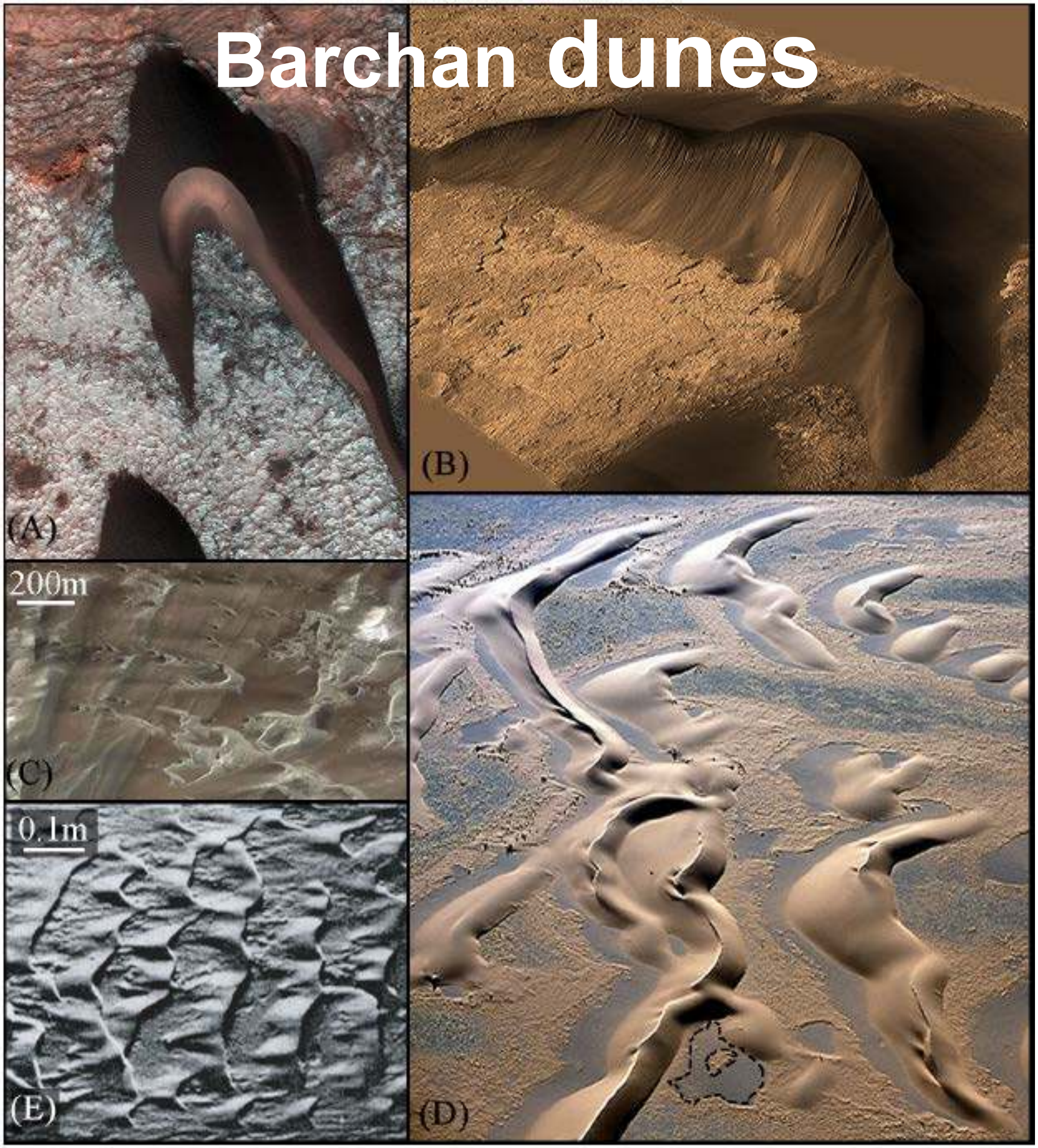
Merging process



t0<t<3600 sec



Barchan dunes



Coupled hydro-morphodynamic LES of barchan dunes in a turbulent open channel flow

A. Khosronejad and F. Sotiropoulos, “On the Genesis & Evolution of Barchan Dunes: Morphodynamics,” *J. Fluid Mech*. 2017

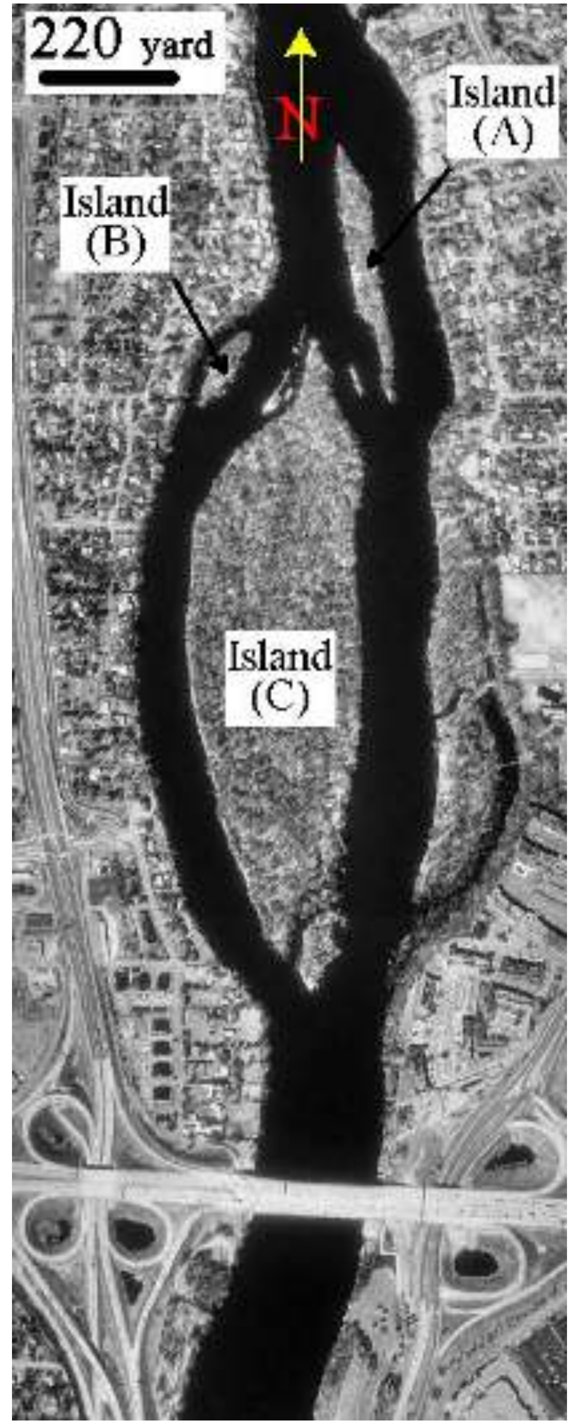
Vorticity magnitude iso-surfaces over evolving barchans

Physical time is accelerated by 200 times

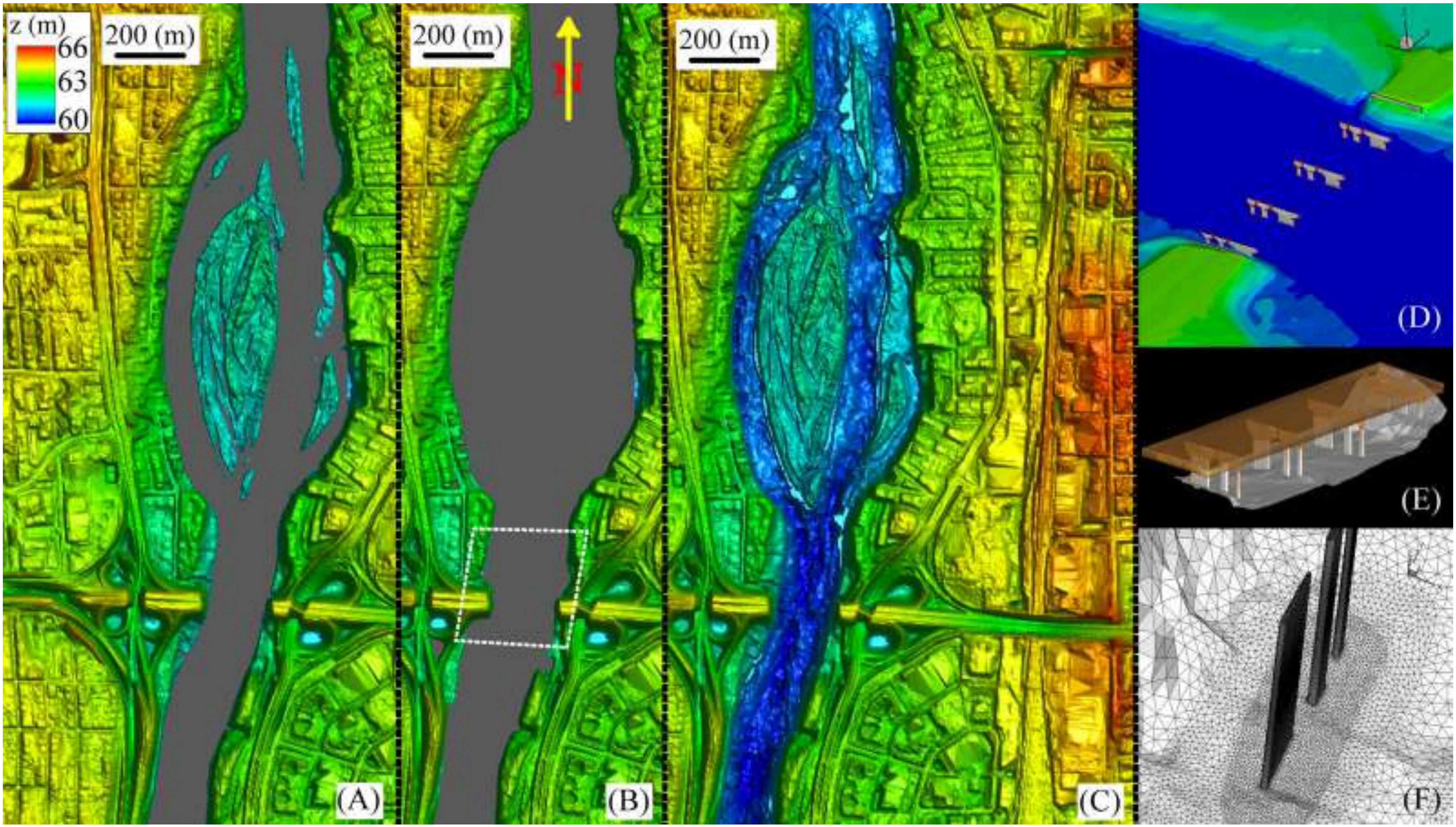
Data-informed simulations of extreme flooding in the Upper Mississippi River

Khosronejad et al., *Adv. In Water Resources*, 2016

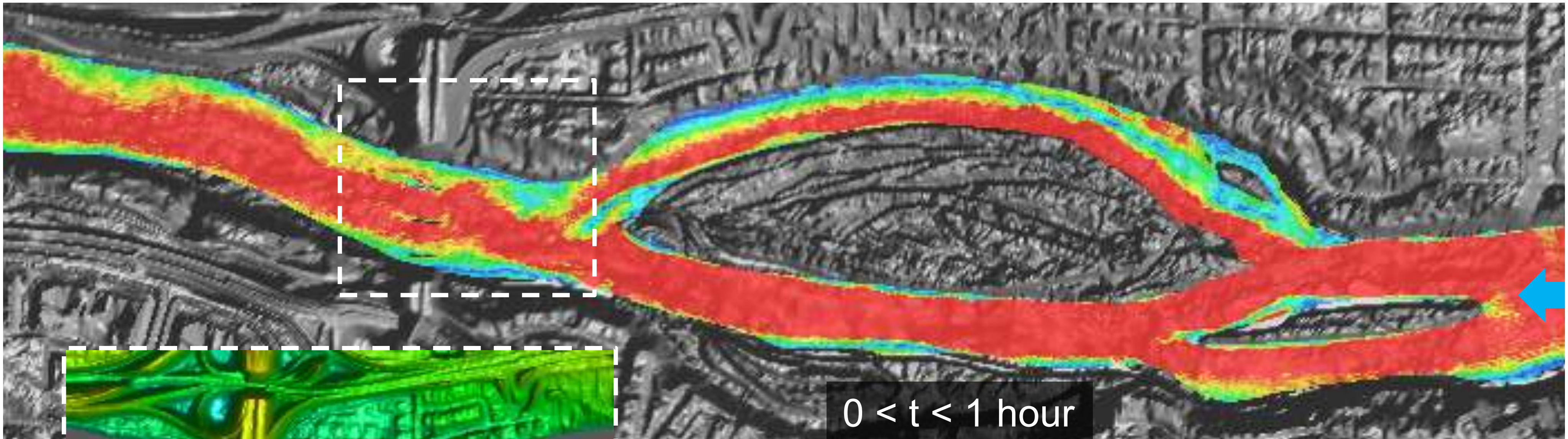
- **Objective:** Finding maximum scour depth under extreme flood conditions of **100 and 500 year-floods**
- **Source of geometrical data:** LiDAR; Sonar onboard a boat; Laser scanner
- **Sources of flow field data for model validations**: Acoustic Doppler Current Profiler (ADCP) onboard a boat

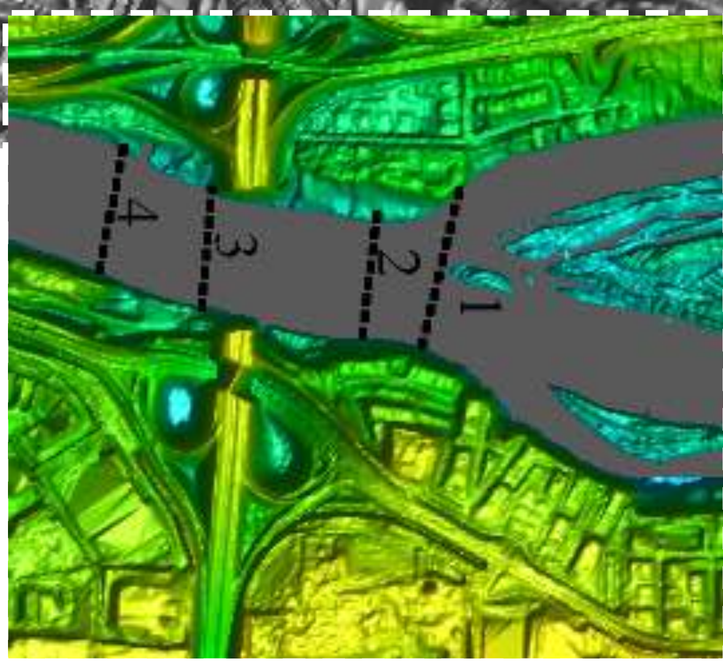


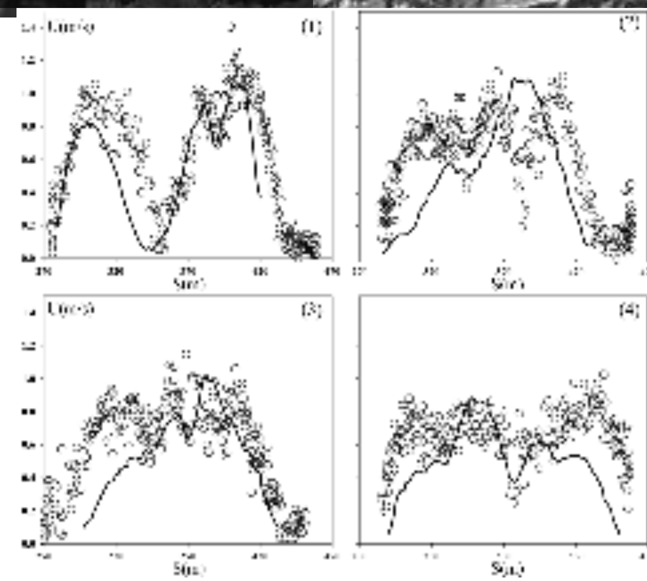
High-resolution digital terrain model by fusing a variety of data sets



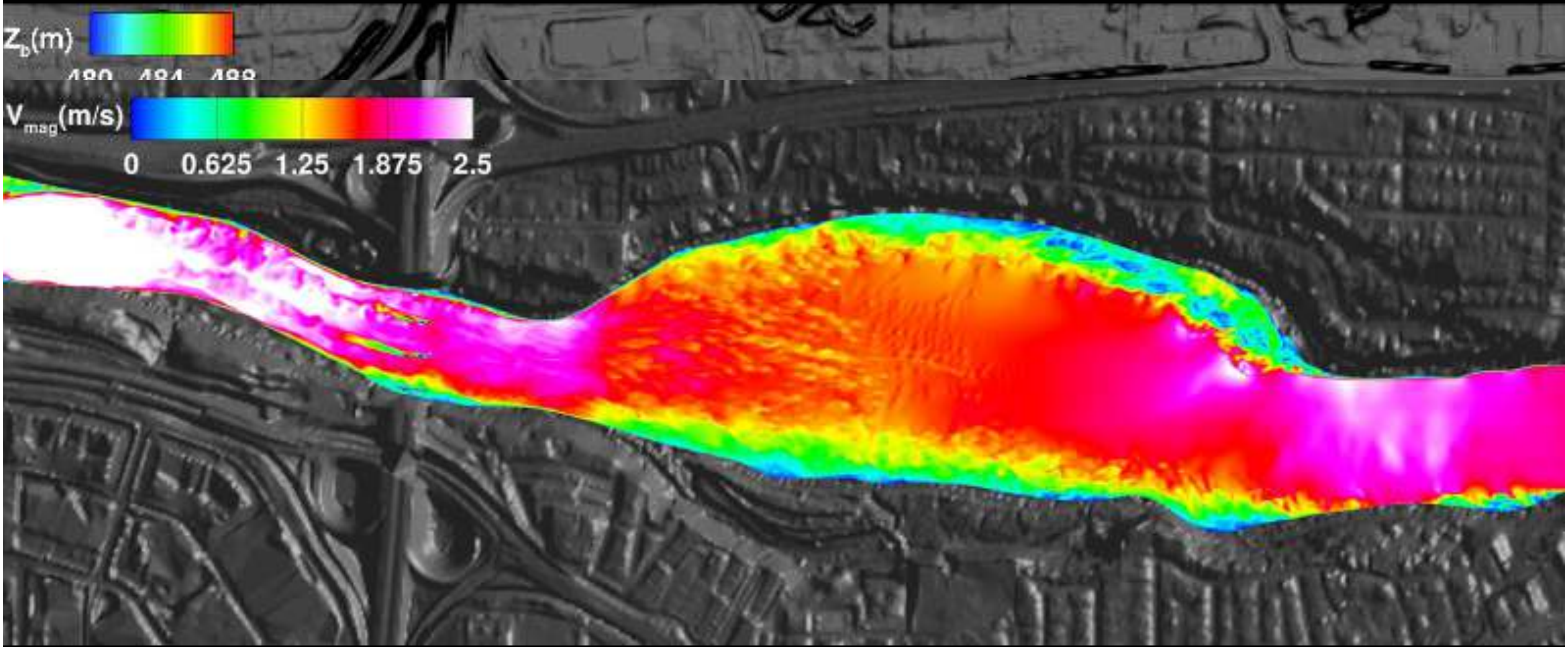
Validation with field measurements under base-flow condition







Hydrodynamics & morphodynamics of a 100-year flood event

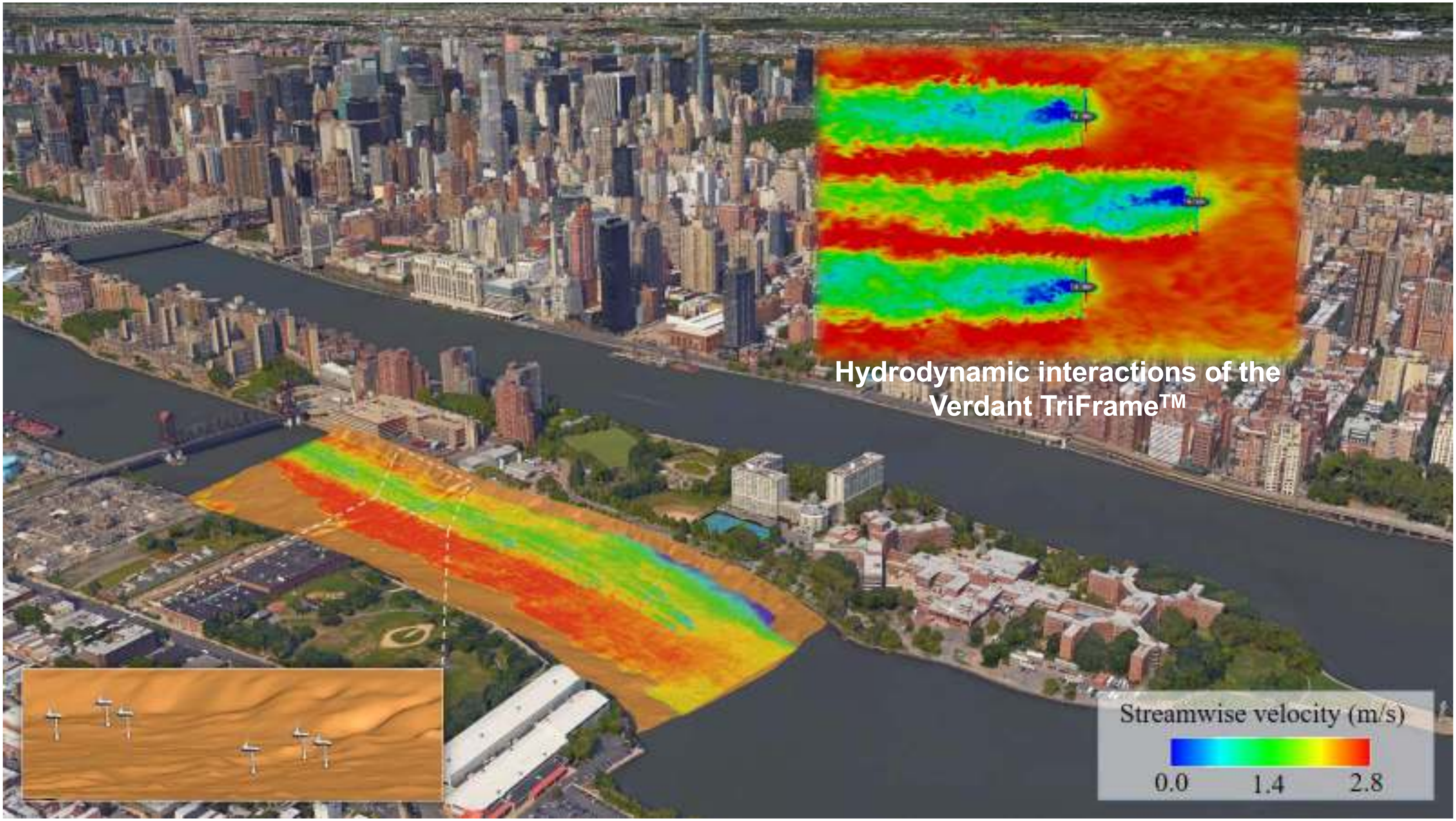


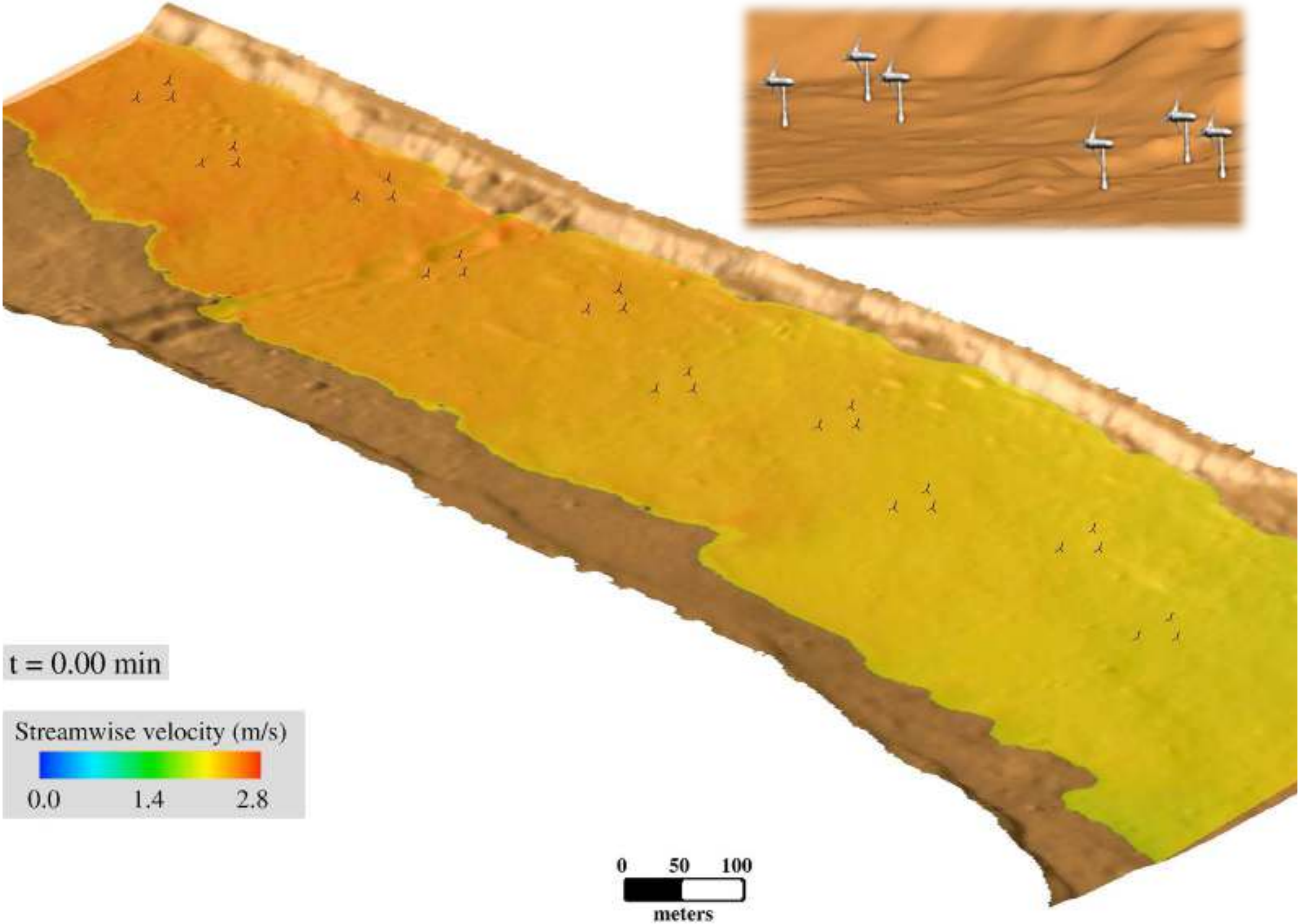
Simulating bridge foundation scour at field scale

Simulation-based optimization of tidal energy

The Verdant Power Roosevelt Island Tidal Energy Project

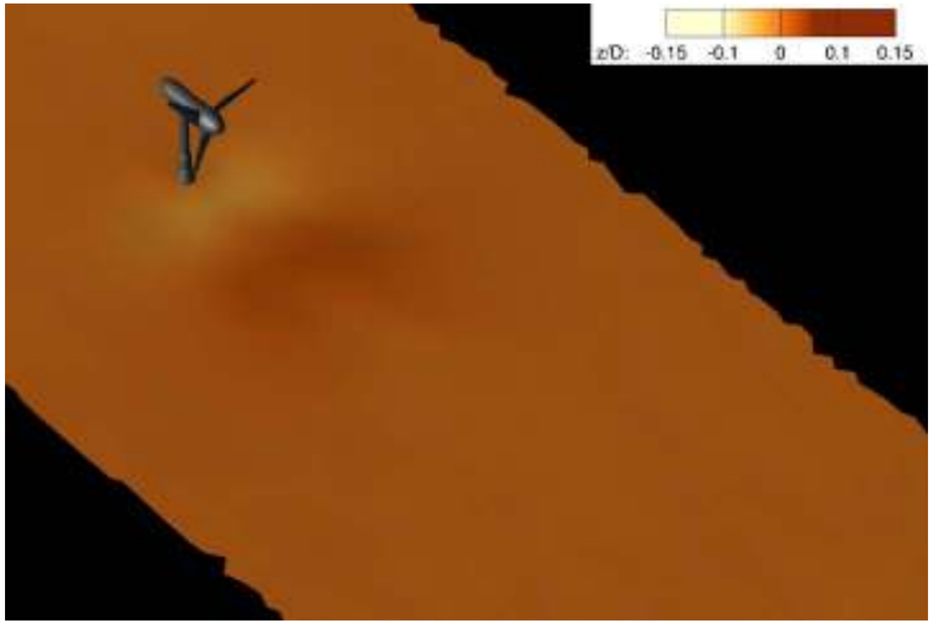
Chawdhary et al., *Water Resources Research,* 2018

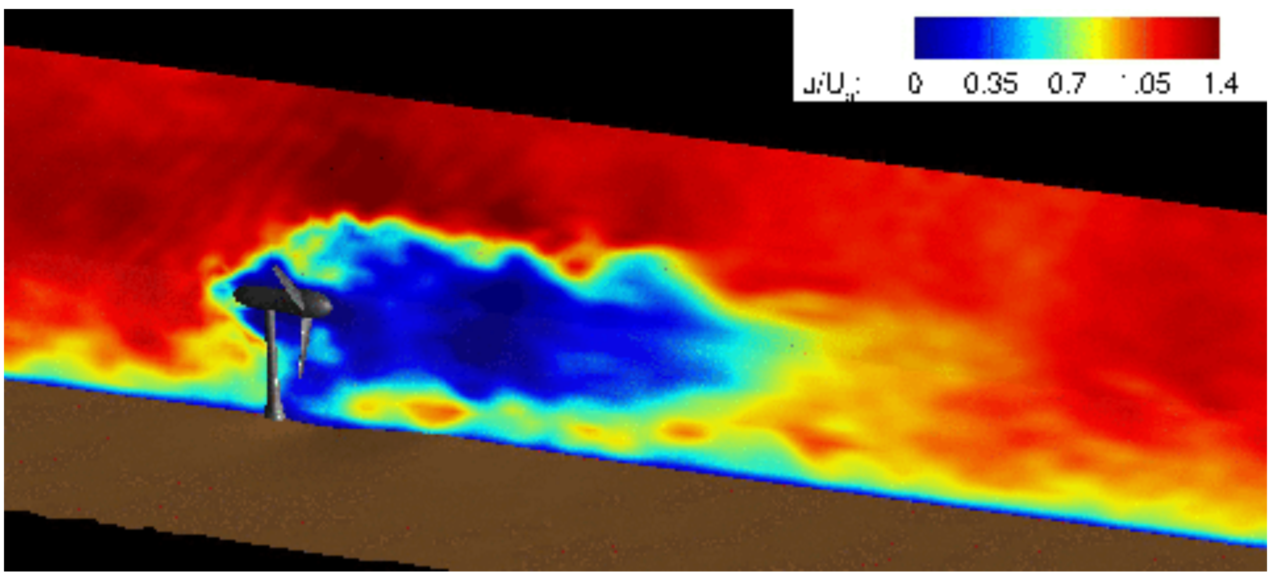



t = 0.00 min
Streamwise velocity (m/s)
0.0
1.4
2.8
0
50
100
meters

Turbine-flow-sediment interactions

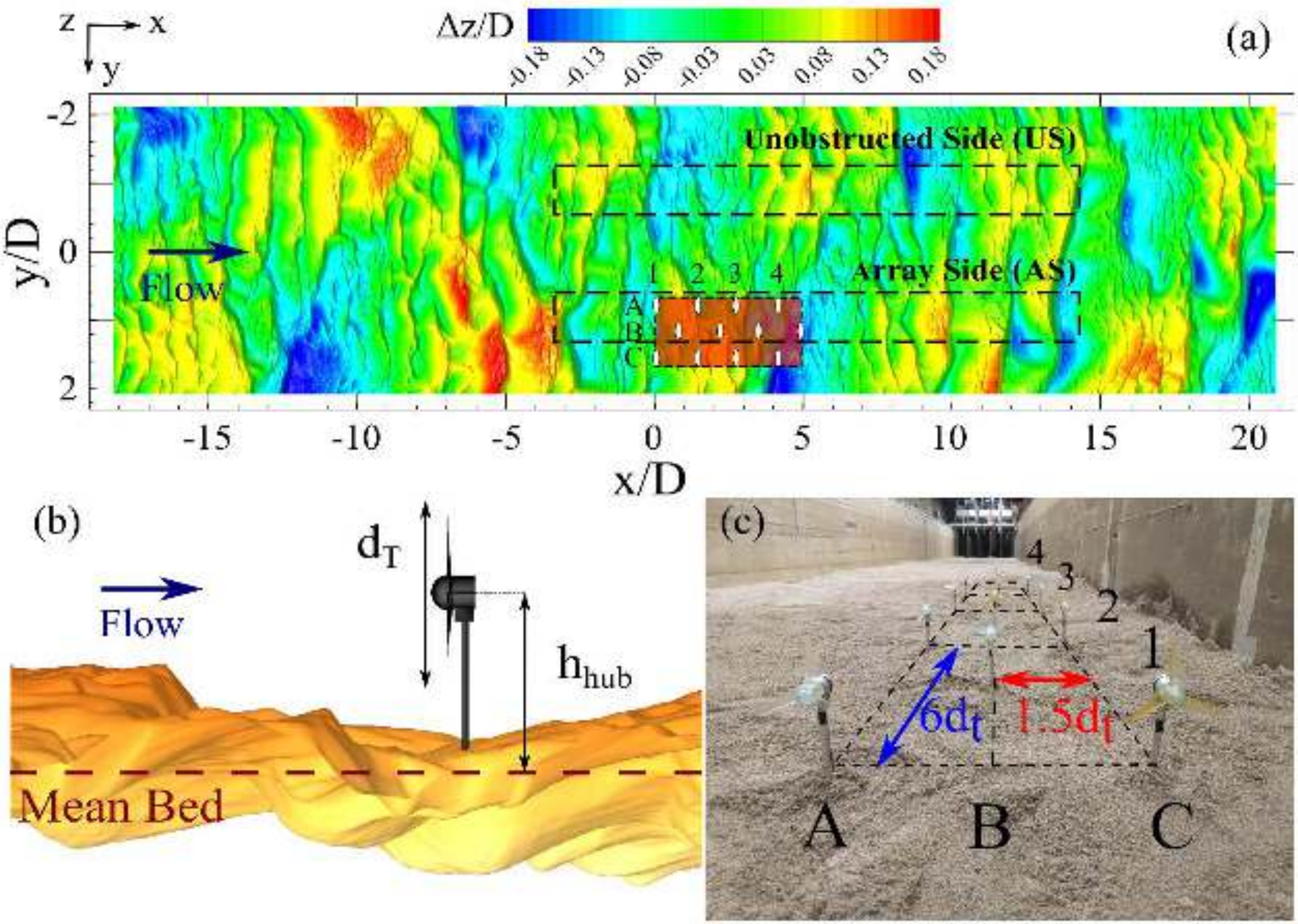
Yang, Khosronejad & Sotiropoulos, *Renewable Energy*, 2017



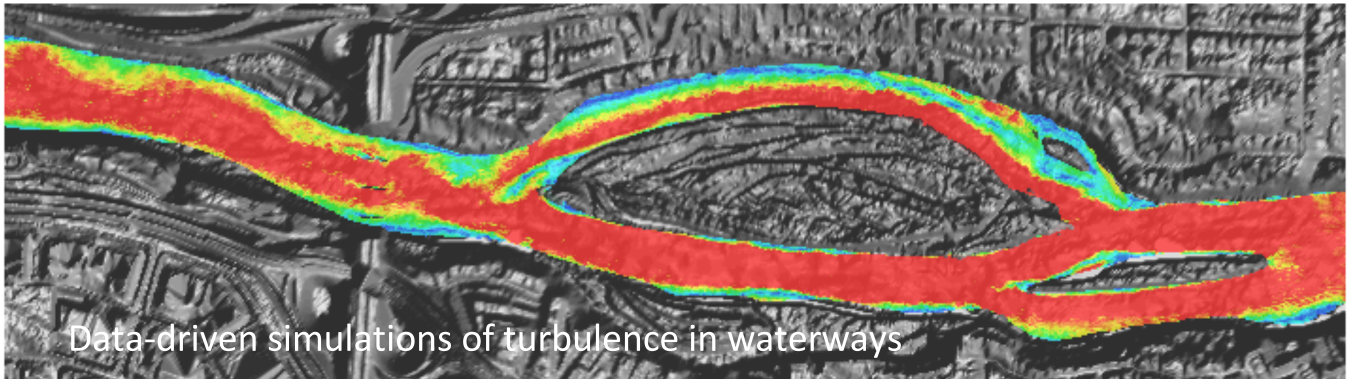


Performance and resilience of hydrokinetic turbine arrays under large migrating fluvial bedforms

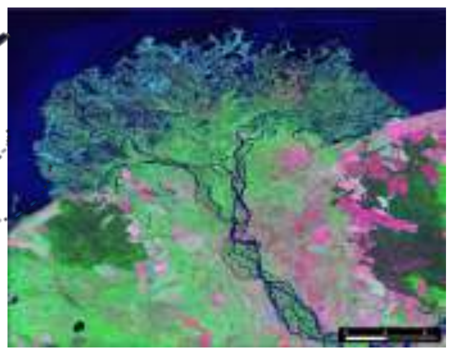
Musa, Hill, Sotiropoulos & Guala, *Nature Energy,* 2018



Fluid mechanics in the era of extreme computing: Cyber-physical systems of natural environments



Site-specific reduced order models for engineering design & decision support: Big-data from measurements and high-fidelity models, Machine learning



Data-driven HPC simulation of ecosystems: Hazard mitigation, water quality, energy harvesting, restoration & sustainability, etc.

Ecosystem scale: Data from satellites and airborne lidars

Local scale: Real-time data from embedded and autonomous robotic sensors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Thank you!