The Origin of Aeolian Dunes:

PIV measurements of flow structure over early stage protodunes in a refractive-index-matching flume

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TOAD: The Origin of Aeolian Dunes

"**Protodunes**": Dunes in their early initiation stages

Objective:

- To understand the genesis and subsequent evolution of aeolian early stage bedforms by quantifying for the very first time the role and importance of flow, transport and surface feedbacks in the initiation and emergence of dunes

Great Sand Dunes National Park

Lab team

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NSF

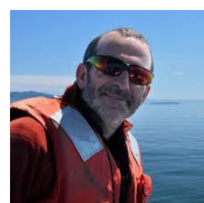
Field team

UNIVERSITY OF Southampton

UNIVERSITY OF OXFORD

Loughborough University

NERC SCIENCE OF THE ENVIRONMENT



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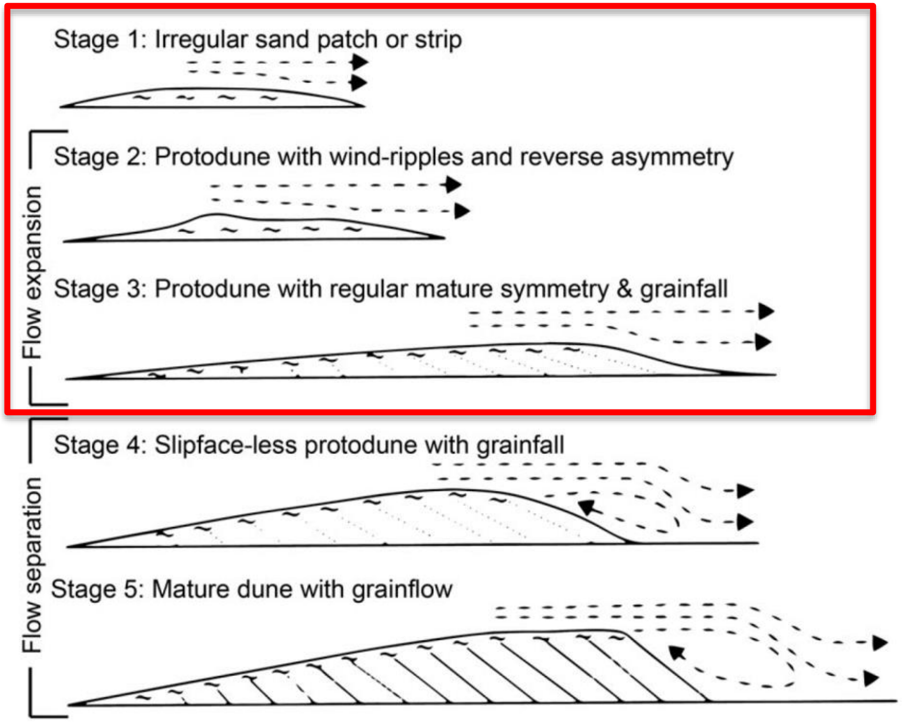
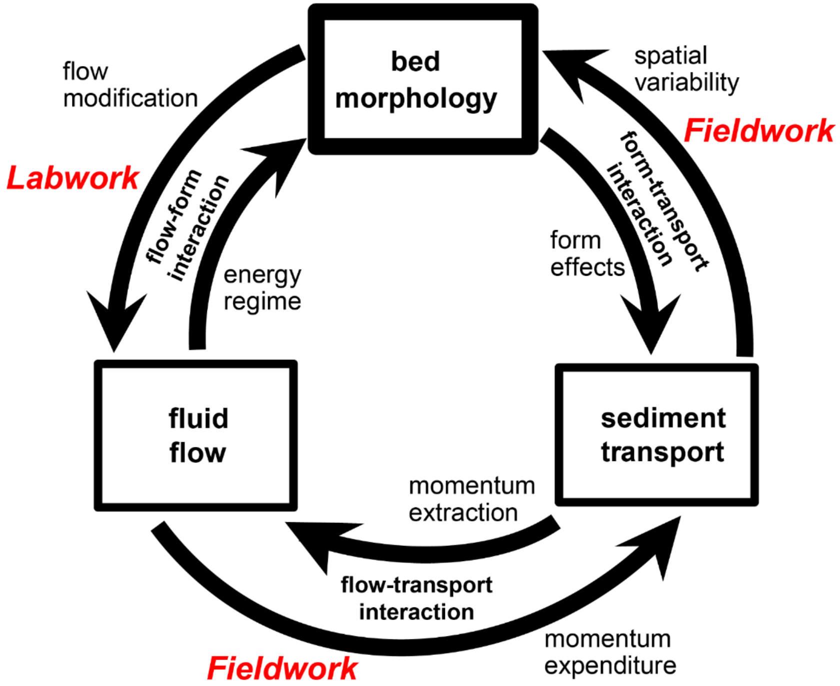
Background and motivation

- Beginning from "patches" of sand, bedforms gradually develop, beginning with reverse asymmetry of more mature dunes

- Emerge and develop out of a complex feedback between overlying fluid flow, transport, and morphology



Kocurek et al. 1992. *J. Sed. Res.*, 62: 622-635



Modified from Livingstone et al. 2007. *Earth-Sci. Rev.*, 80: 239-257

Motivation:

- Physical mechanisms behind initiation and development of aeolian dunes are yet poorly understood
- Lack of quantitative data concerning these processes due to challenges in field

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Data from the field

- Morphology: Terrestrial Laser Scanner
  - Millimeter scale resolution
  - Repeatedly measure bedforms developing on the order of minutes
  - Can also measure
    - saltation layer height
    - Moisture
- Sediment transport
  - Sensit (piezoelectric sensor)
  - Wenglor (laser gate)

- Flow
  - Hotwire anemometers
    - Measure mean velocity only
  - 2D and 3D sonic anemometers
    - Measure turbulence and mean velocities
- **Role of the lab**
  - Provide more complete understanding of flow-form interactions in early development stages using access to whole-field measurements (PIV)

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From field to flume: creating idealized protodunes

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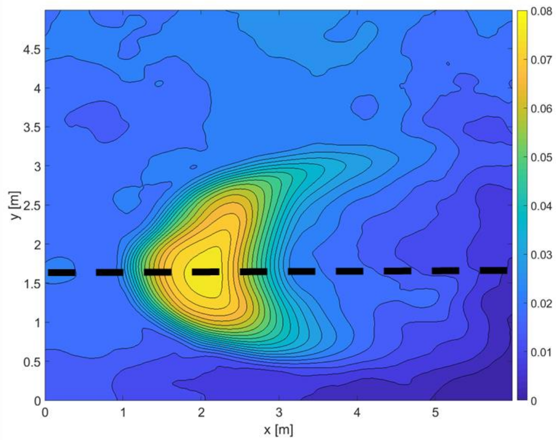
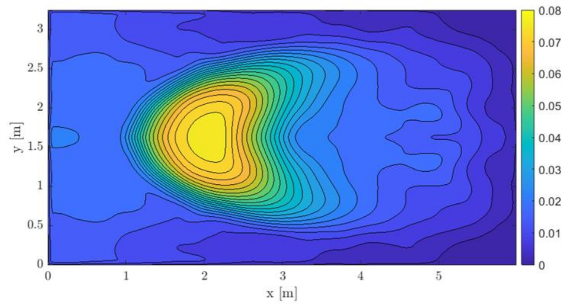
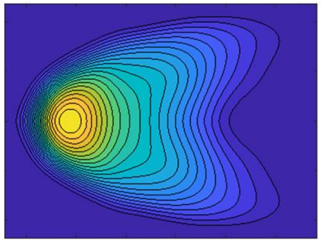
Field protodune → Made symmetric → Final idealized cases

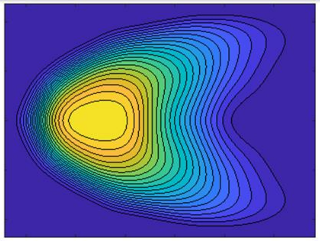






Crest-UP

Preliminary results



Crest-MIDa

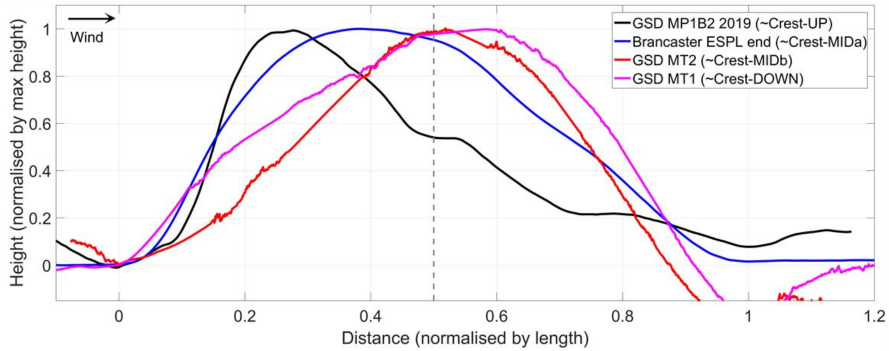
Field dimensions

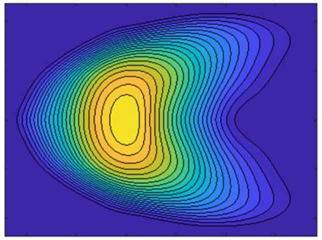
W = 225 cm
H = 5.91 cm

Flume scaling

W = 20 cm
H = 5.25 mm
AR~38:1

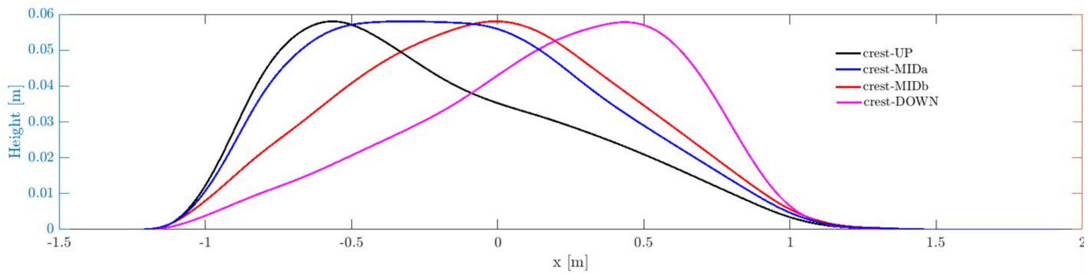
Field morphologies

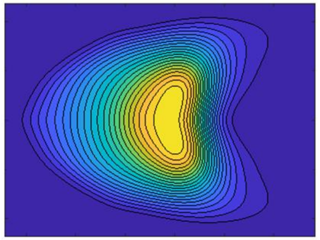




Crest-MIDb

Idealized cases





Crest-DOWN

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Laboratory: Refractive-index-matching (RIM) flume

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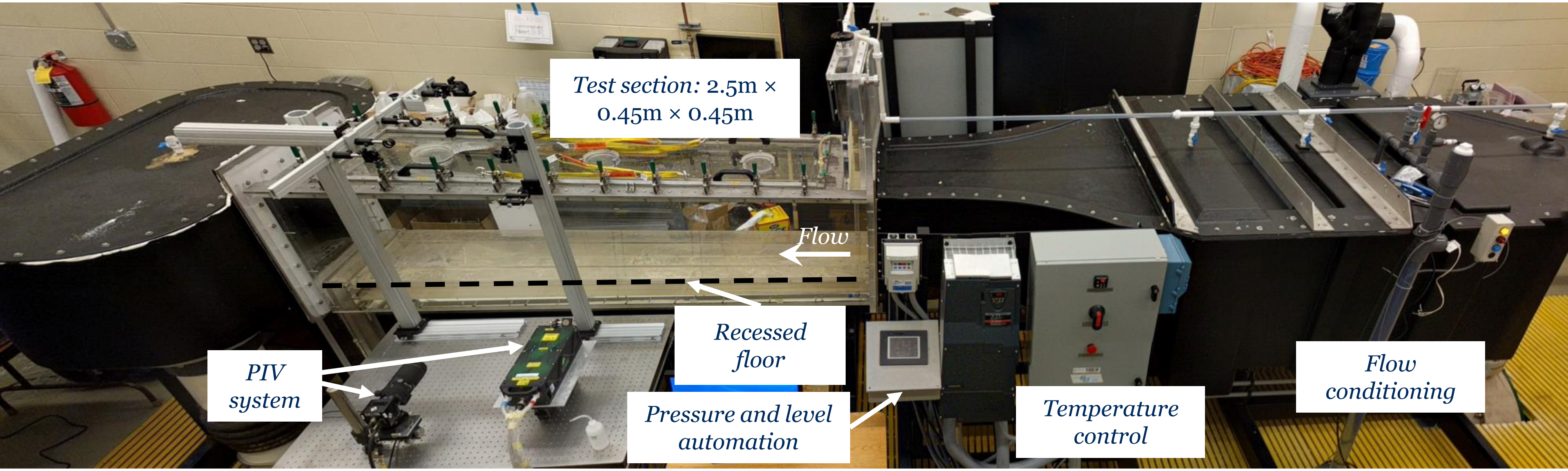
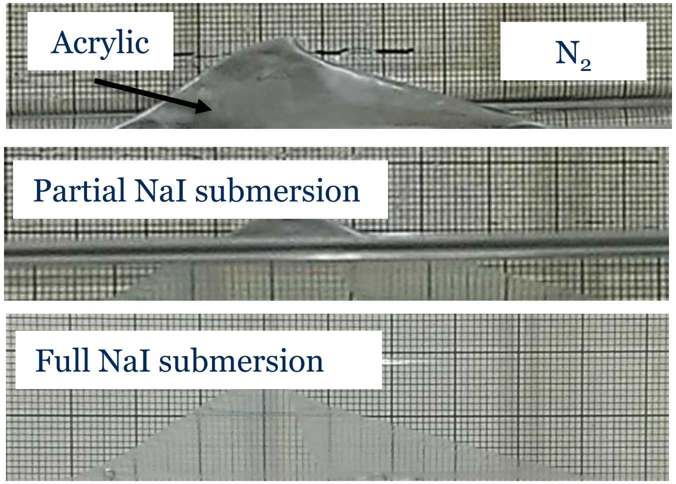


- RIM benefits
  - Optical access to flow field
  - Mitigation of laser reflections which hurt near-surface measurements
- Facility:
  - Corrosion resistant
  - Sealed from atmosphere
  - Temperature control
  - **No mobile sediment, only solid models**

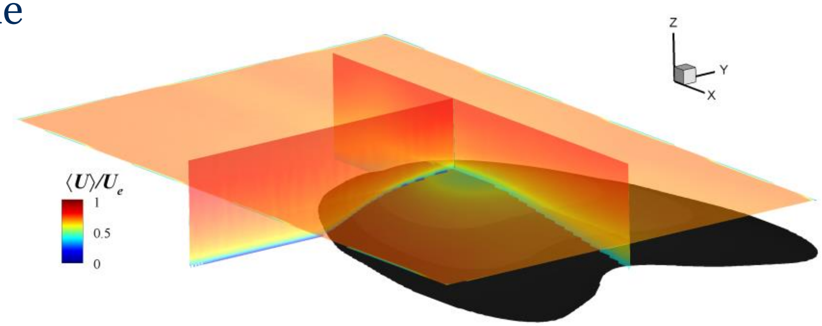
<u>Refractive-index-matching</u>

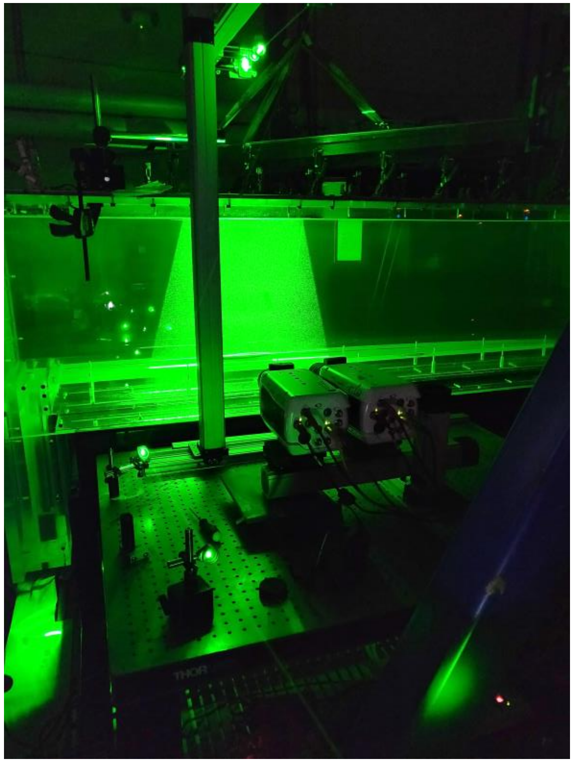


Blois et al. 2020. *J. Hydraul. Eng. 146(5), 04020033*

Laboratory measurements

- Particle image velocimetry (PIV): optical technique for non-intrusive measurement of flow velocity components in 2D planes
  - Streamwise-wall-normal (*x-z*)
  - Streamwise-spanwise (*x-y*)
  - Cross-stream *(y-z)*
- Temporal resolution
  - Low frame rate for time-averaged flow statistics
    - 0.5 Hz
  - High frame rate for looking at dynamics
    - 700 Hz
- Flow conditions
  - **No sediment in flume**
    - Using solid plastic models, enabling RIM approach
  - Protodune model attached on smooth acrylic floor
  - Turbulent boundary layer thickness, δ = 46 mm
    - Tripped at inlet
    - $H/\delta \approx 0.11$
  - Reynolds number, $Re_\tau = 1600$
  - Free stream velocity, $U_e = 0.97$ m/s
  - Friction velocity, $u_\tau = 0.0384$ m/s





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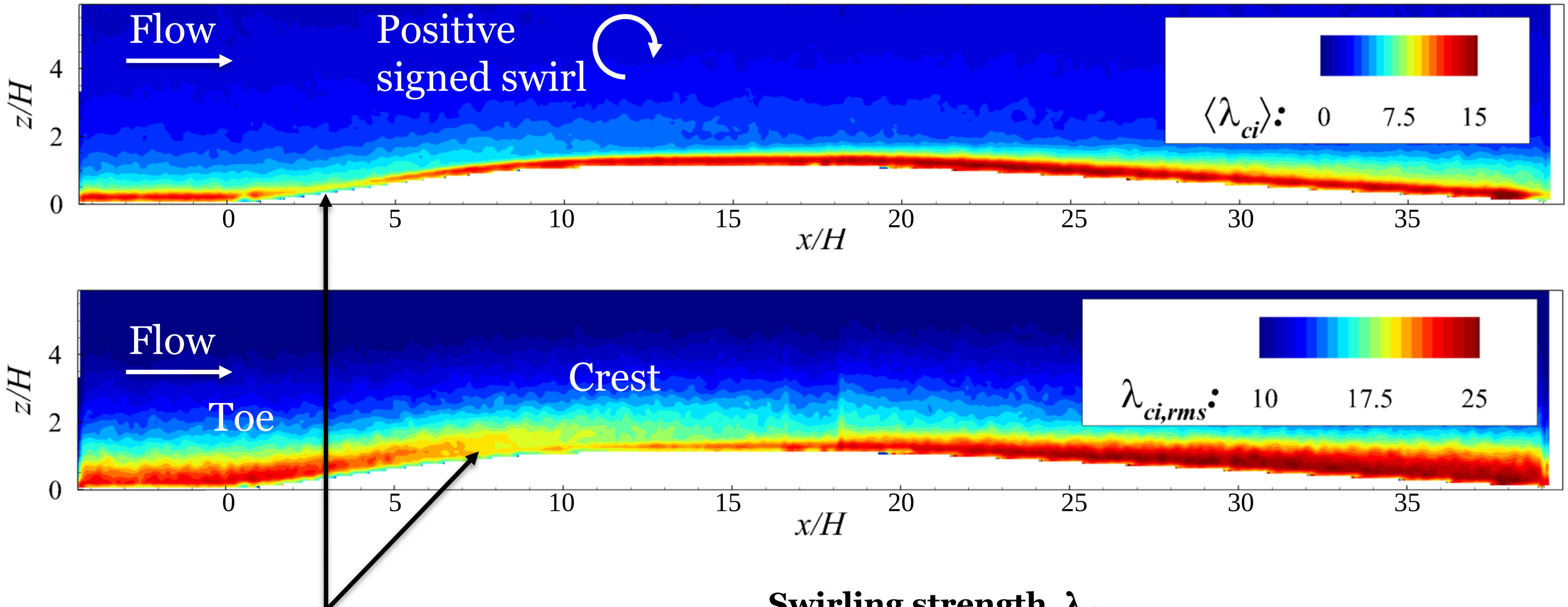
Protodune impacts vortex organization

Streamwise-wall-normal (x-z) plane along centerline



Changes over protodune suggests either a reorientation of swirling direction as flow passes over protodune (only spanwise component of swirling is measured in this plane)

Swirling strength, λ_{ci}

- Similar to vorticity, measures local rotation (independent of convection velocity)
- Mean $\langle\lambda_{ci}\rangle$: indicates strength of bias in rotational direction
- Root-mean-square $\lambda_{ci,rms}$: indicates characteristic intensity of swirling

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Swirling strength profiles

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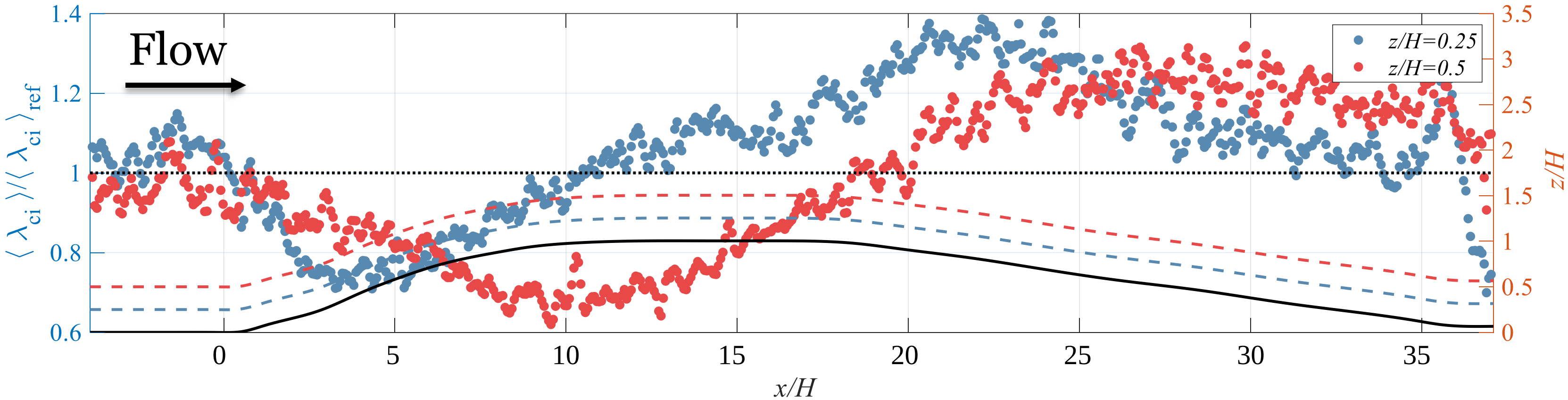
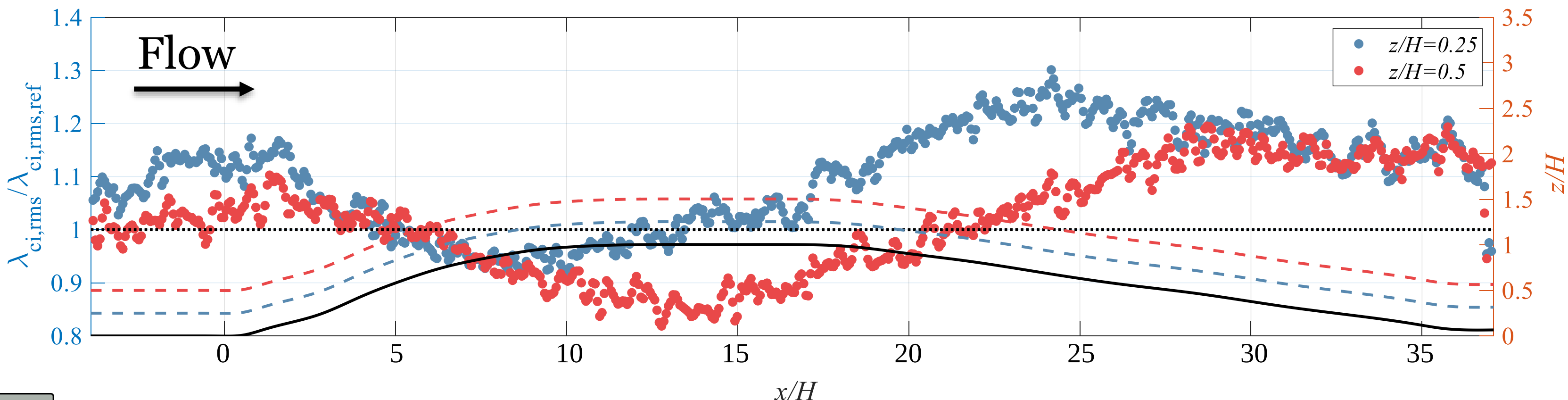
Trends or previous slide more clear through horizontal profiles of data extracted from constant elevation (indicated by dashed lines)

Profiles are normalized by reference data taken without dune model in flume





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Linking aeolian streamers to protodune development

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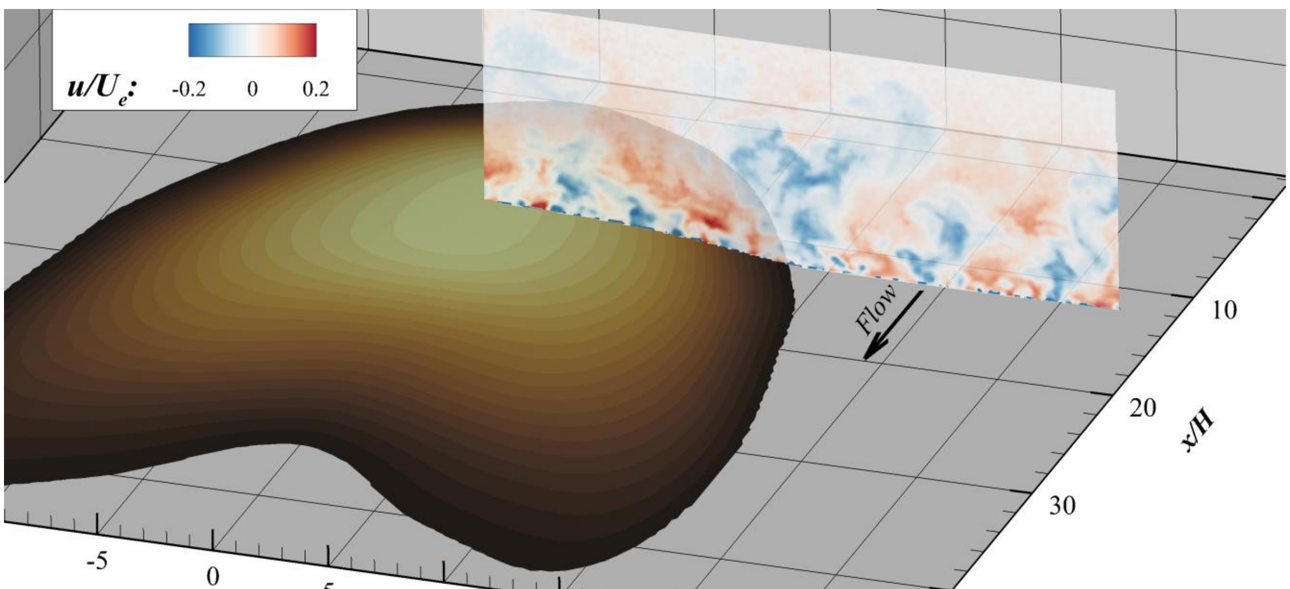
- Question:
  - **Do perturbations to the organization of sand streamers control deposition patterns (i.e., protodune initiation and development)?**
- Approach:
  - Assume that streamers are linked to large-scale turbulence structures
  - **Investigate changes to the spacing and widths of large-scale turbulent flow structures overlying the protodune in the flume**



Color contours of streamwise velocity fluctuations in an instantaneous snapshot of flow

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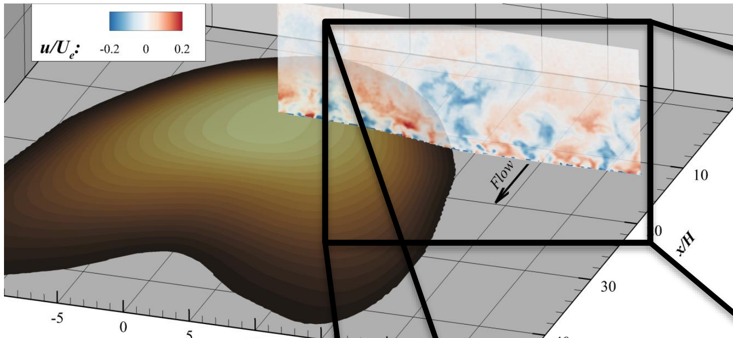
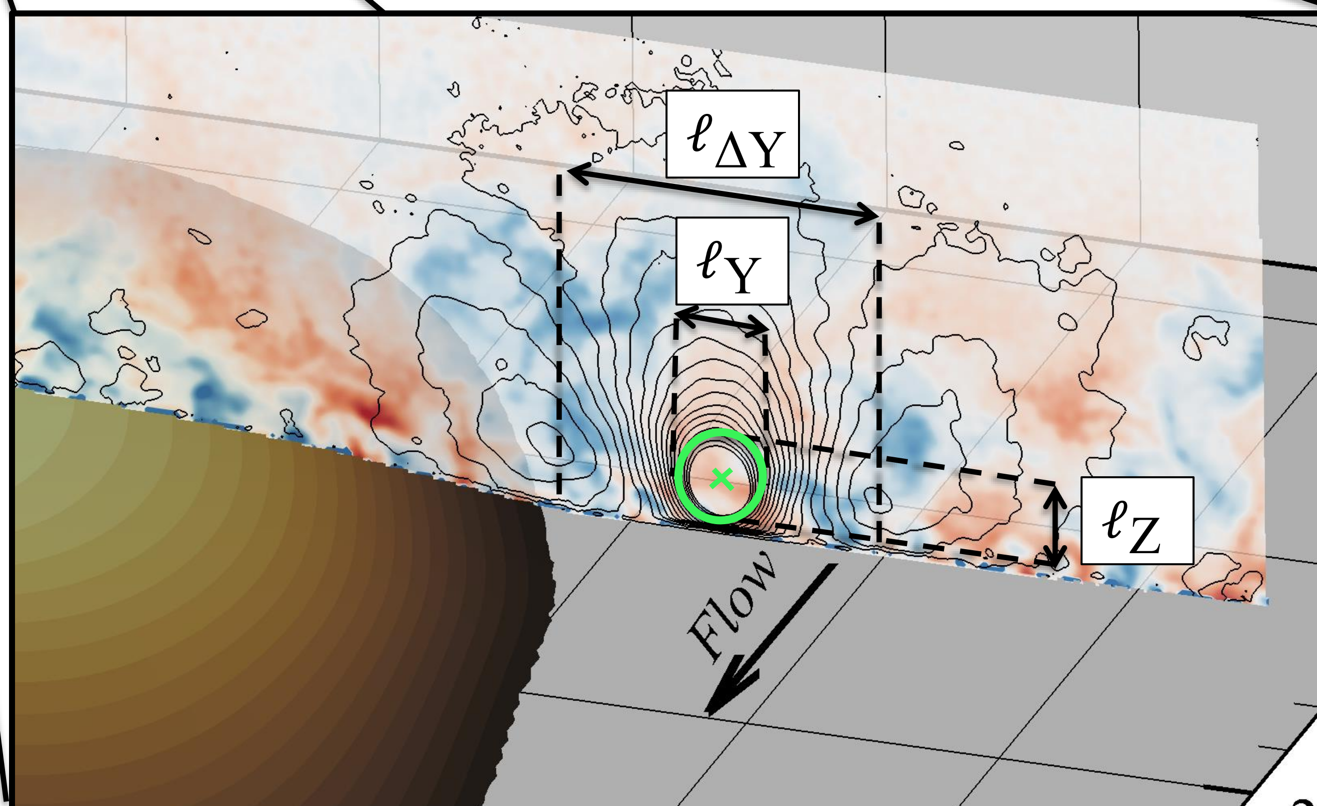
Calculating lengthscales using correlations



Contour lines given by autocorrelation coefficient of streamwise velocity fluctuations:

$$\rho_{uu}(\boldsymbol{x}_{\boldsymbol{ref}}) = \frac{R_{uu}(\boldsymbol{x}_{\boldsymbol{ref}})}{\sigma_u(\boldsymbol{x}_{\boldsymbol{ref}})\sigma_u(\boldsymbol{x})} = \frac{\langle u(\boldsymbol{x}_{\boldsymbol{ref}}, t)u(\boldsymbol{x}, t)\rangle}{\sigma_u(\boldsymbol{x}_{\boldsymbol{ref}})\sigma_u(\boldsymbol{x})}$$



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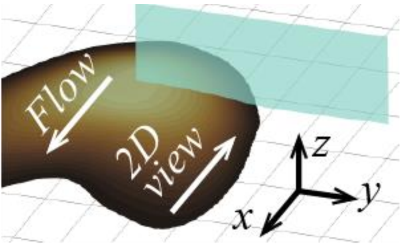
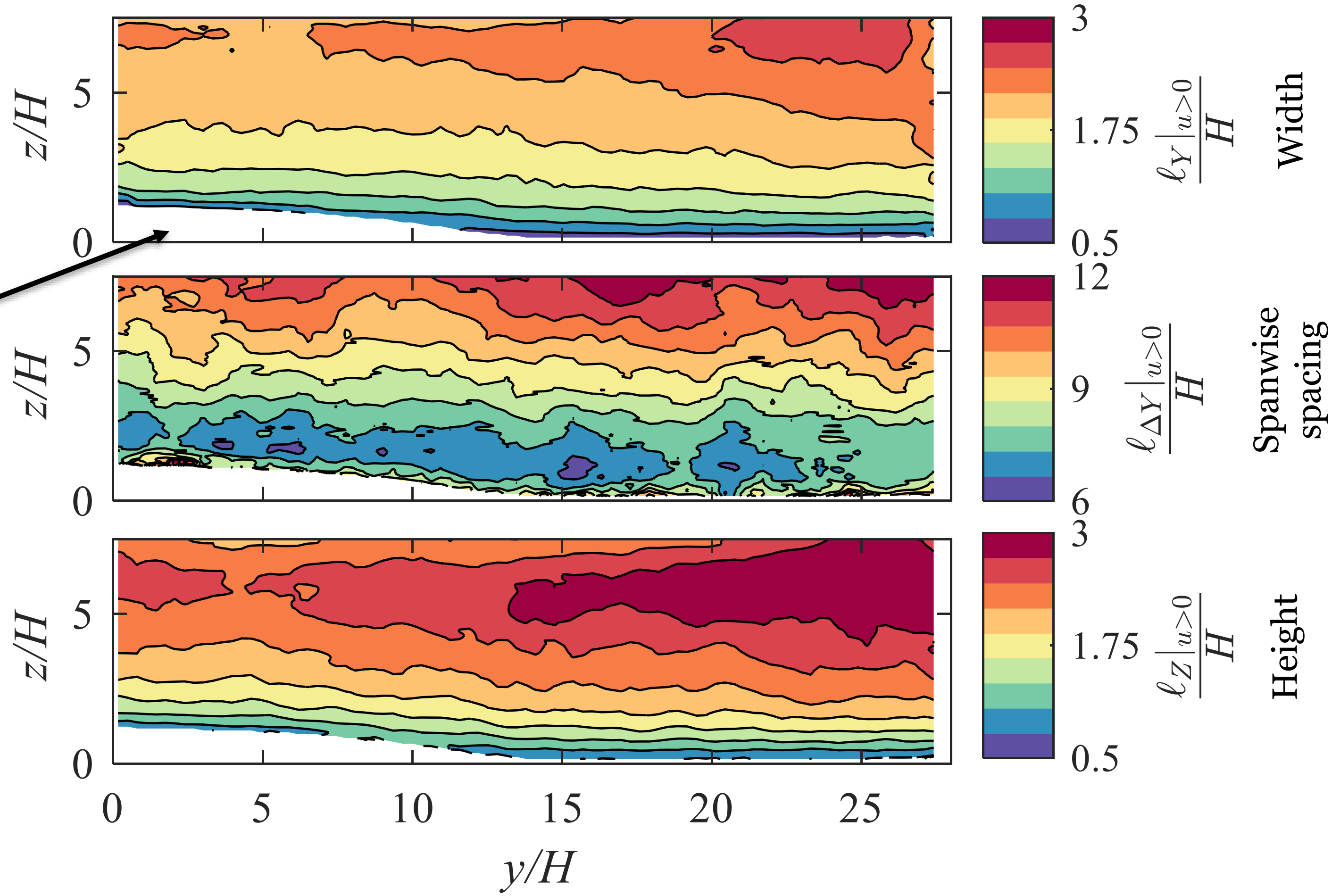
Lengthscales calculated at each grid point



Bedform masked out



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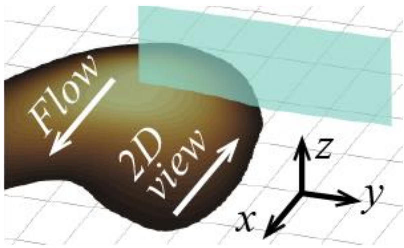
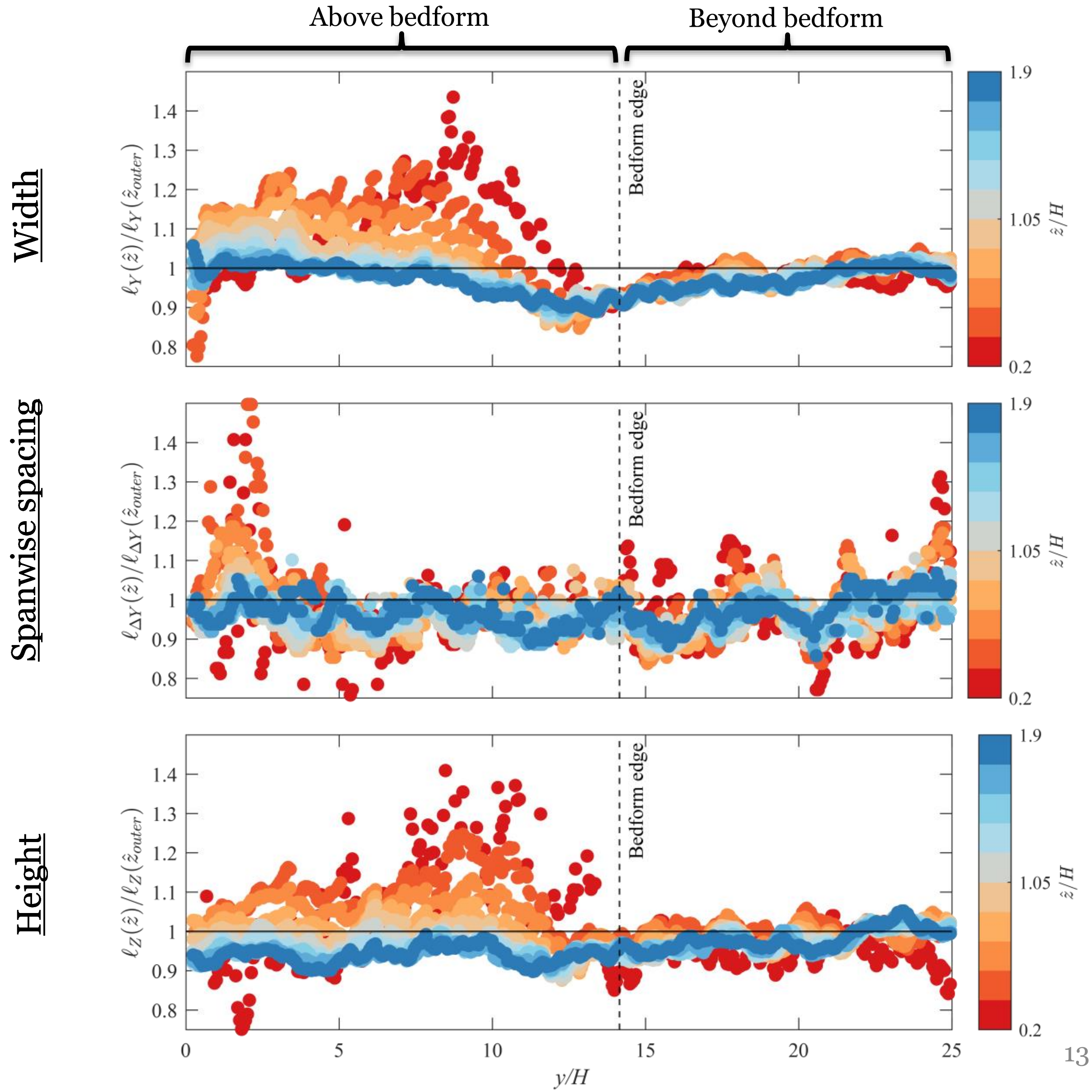
Constant elevation profiles of lengthscales



- ~20-30% increase in correlated spanwise and vertical scales over protodune within 1*H* height above bedform
- Reduction in width where topography of the bedform ends
- Hard to discern clear trend in influence on spanwise spacings by protodune



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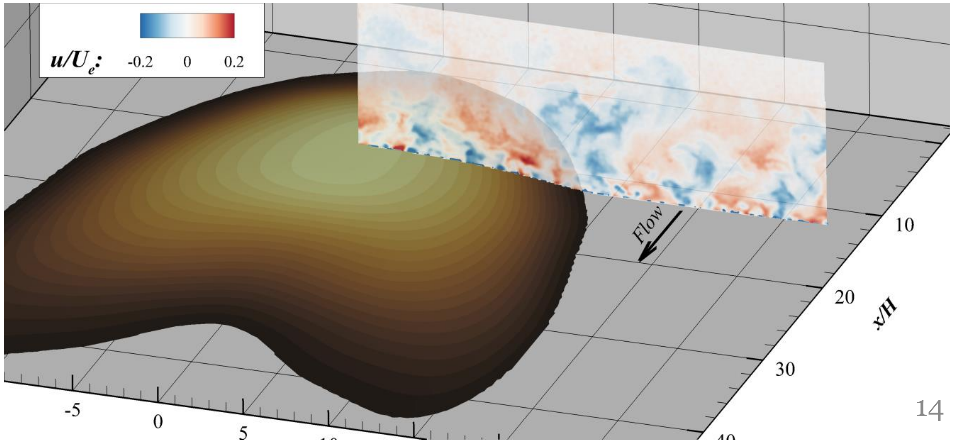
Summary

- Idealized protodune models are scaled down in the lab to study flow-form feedbacks
- Organization of vortices in the boundary layer is altered by three-dimensionality of protodune
- Large-scale turbulent flow motions (likely linked in the field to streamers) are also modified in their lengthscales as they pass over the protodune, growing wider
- Spacings between large-scale motions seem largely unchanged by protodune



Appendix

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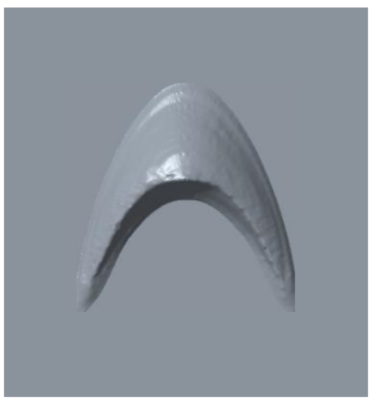
Model fabrication

- Example from prior work with barchan dunes:



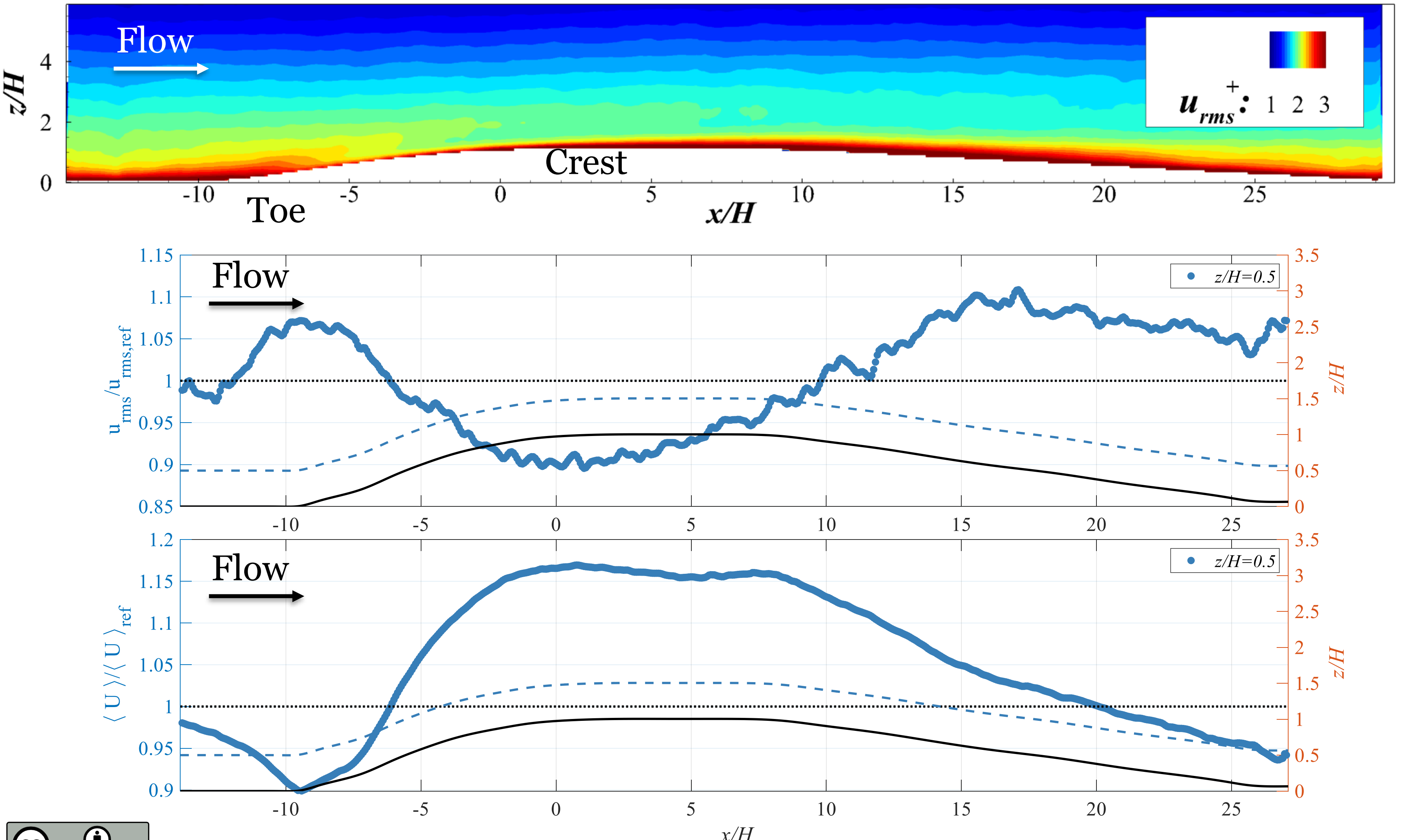
CAD model

3D printed (positive)

Silicone rubber mold (negative)

Urethane model (positive)

Mean velocity and turbulence modified over crest



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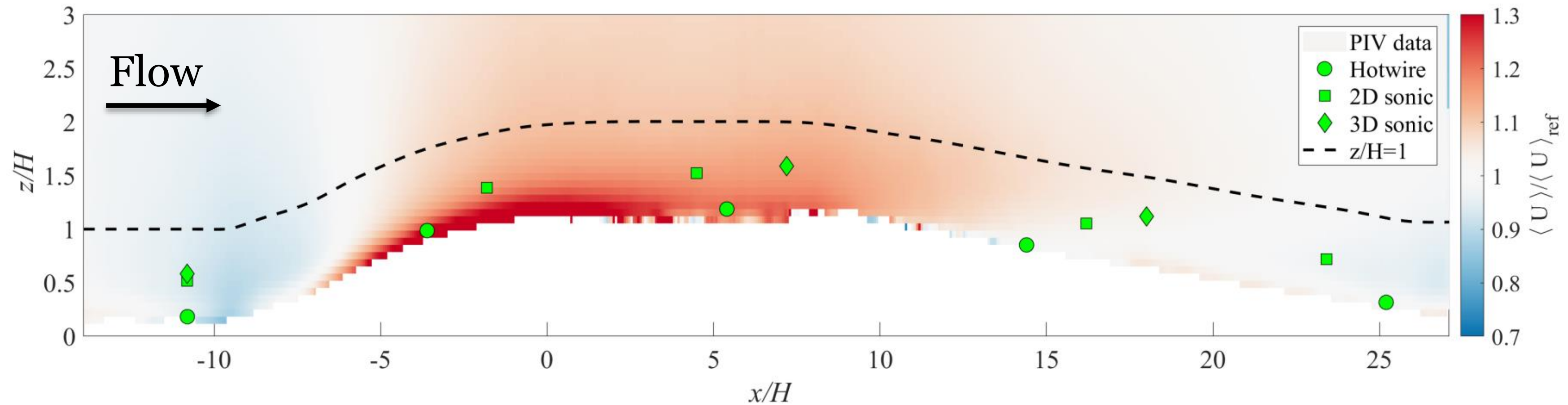
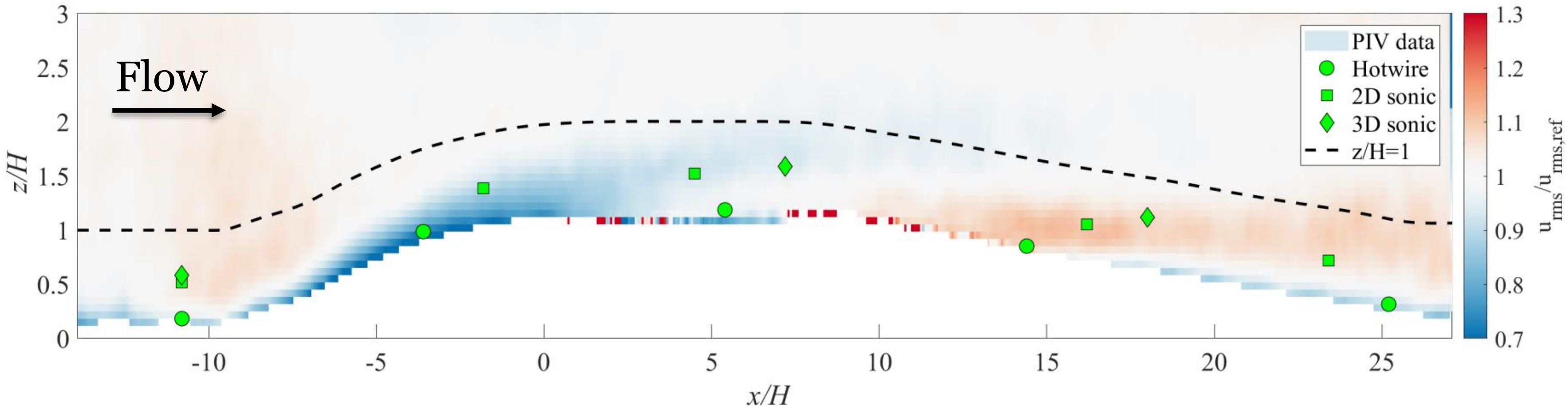
Informing data collection in the field





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