The influence of dune lee side shape on flow above bedforms

Alice Lefebvre

MARUM – Center for Marine Environmental Sciences

University of Bremen, Germany

alefebvre@marum.de

@DrAliceLefebvre

Julia Cisneros

Texas A&M University

University of Texas at Austin

Texas Tech University

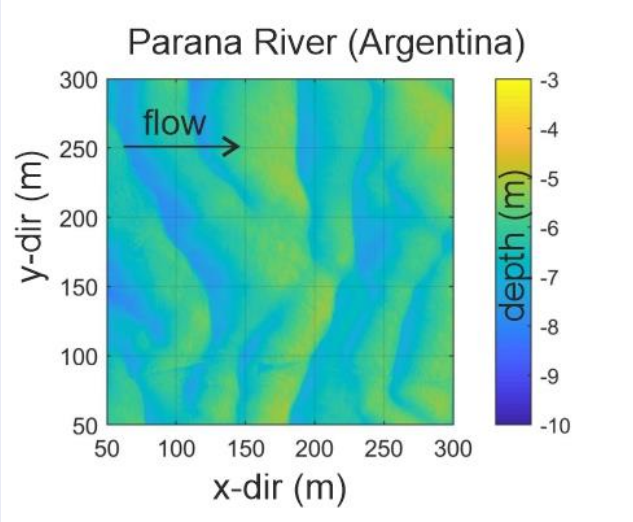
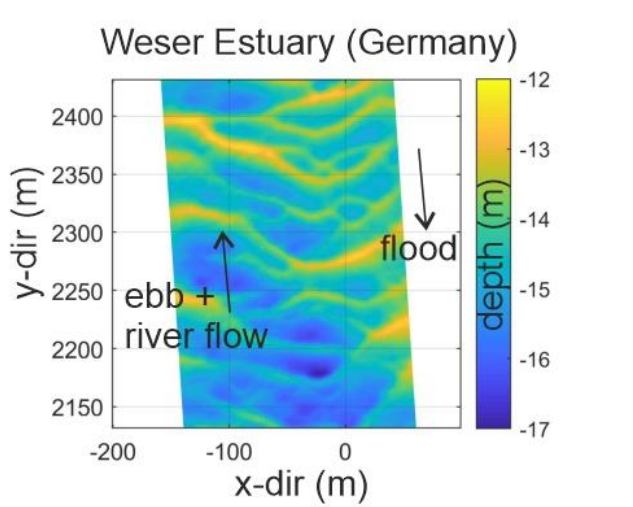
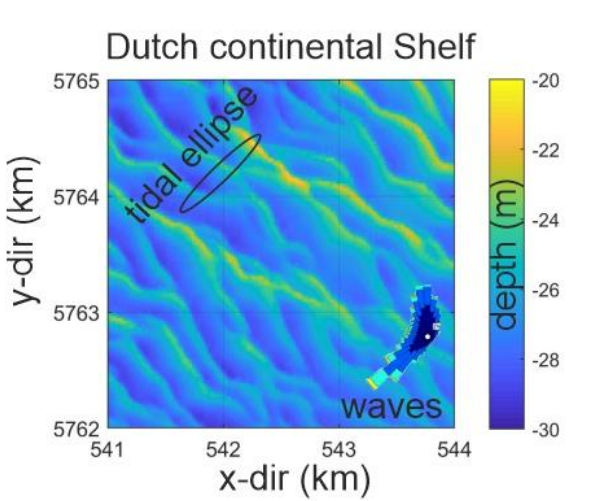
jcisneros1024@gmail.com

@Juliamorphology

Universität Bremen

marum Center for Marine Environmental Sciences

Underwater dune types

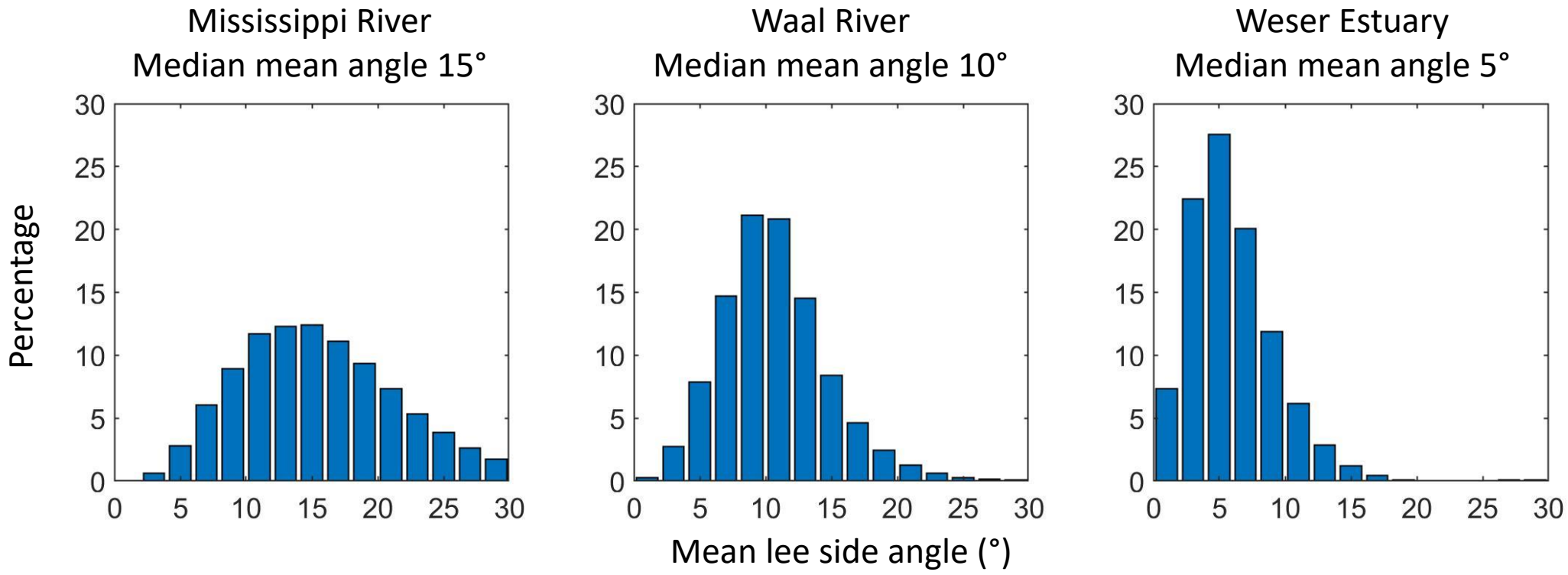
Bedform type	River and flume dunes	Estuarine and tidal dunes	Marine dunes / sand waves
Environment	Unidirectional & constrained	Bidirectional & constrained	Open
Forcing	River flow	Tidal currents, River flow Other currents	Tidal currents Waves Other currents
Example			

Lefebvre and Cisneros, EGU22 https://meetingorganizer.copernicus.org/EGU22/EGU22-3370.html

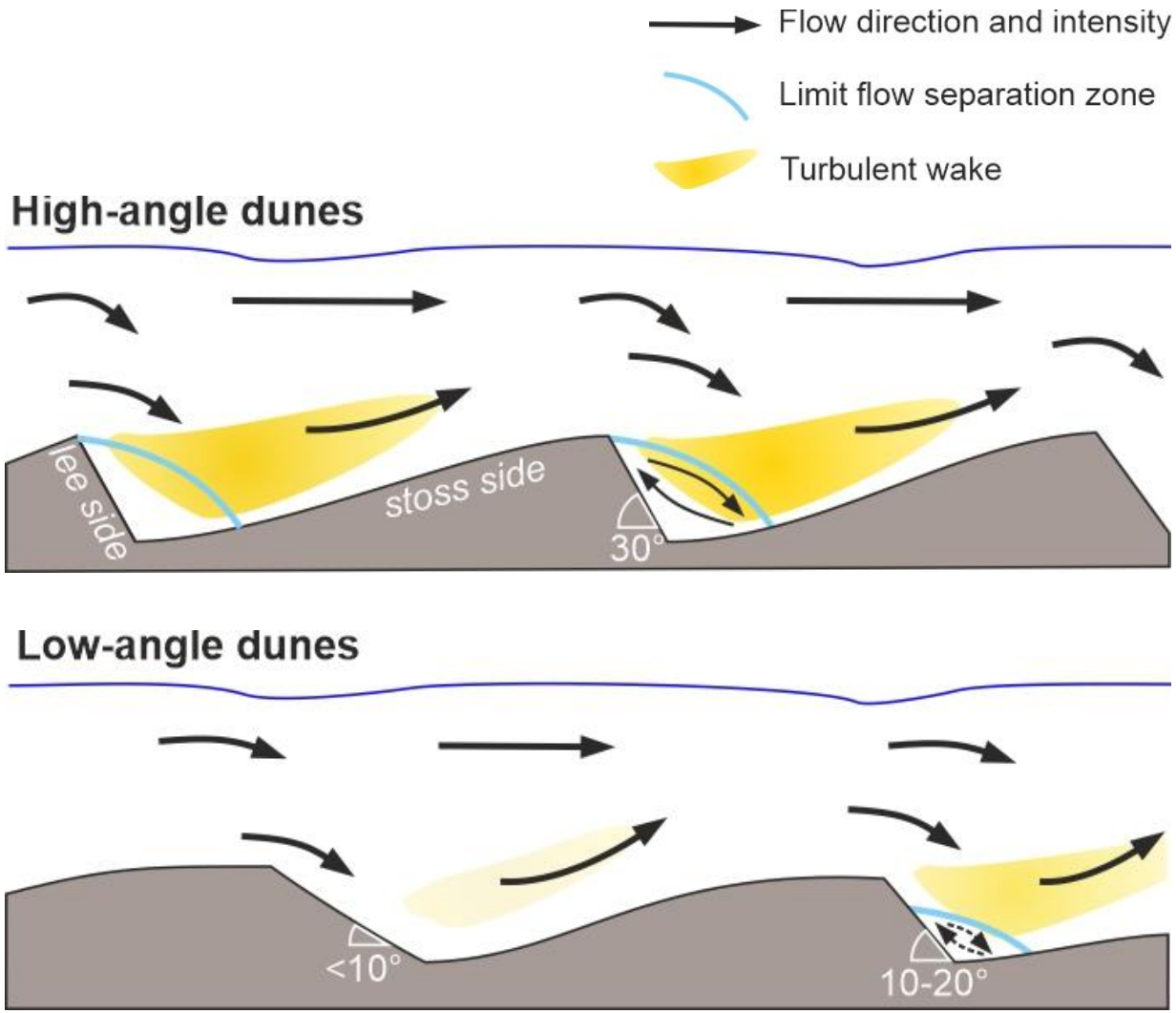
Underwater dunes have low-angle lee side

Until recently, most studies focussed on **high-angle dunes** with lee sides close to 30°.
These dunes commonly form in small rivers and in flumes.

However, dunes in large rivers, as well as in estuaries and marine environments are mainly **low-angle dunes** with lee side angles of less than 20°



Different flow patterns over high and low-angle dunes



Lee side angle has a strong influence on the interaction between dunes and flow

Over **high-angle dunes**, typically with a steep lee side slope (> ca. 25°), the flow separates and a strong turbulent wake is formed

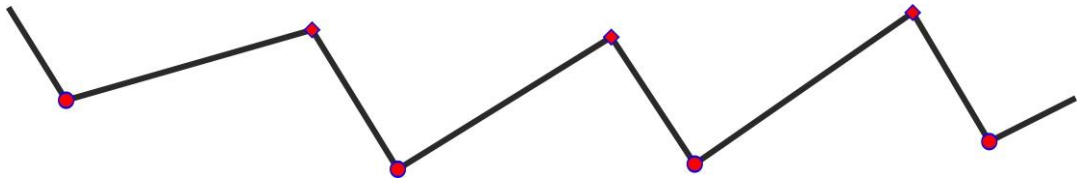
Over **low-angle dunes**, two cases can be distinguished:

if the slope is between ca. 10° and 20°, flow separation is reduced or intermittent and the wake is small and weak.

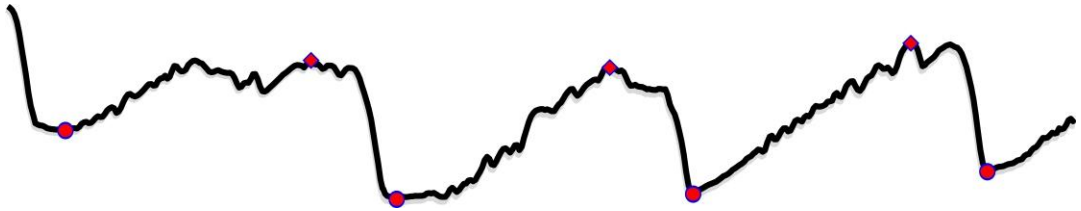
Over angles less than ca. 10°, there is no flow separation and only little turbulence produced

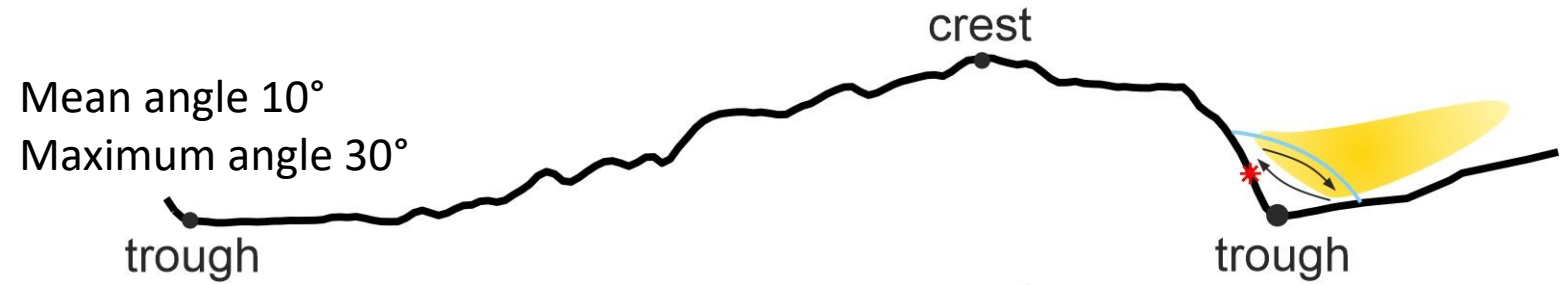
Lee side is not a straight line!

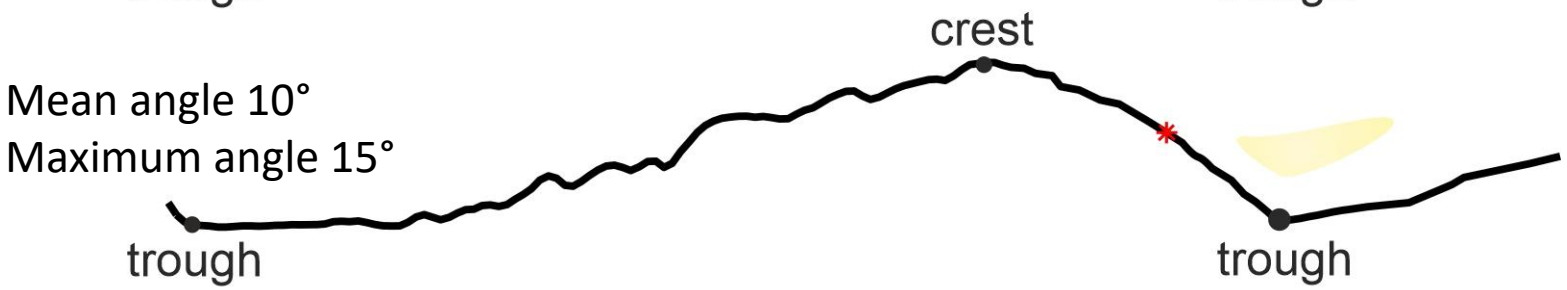
What we think dunes look like



What they really look like







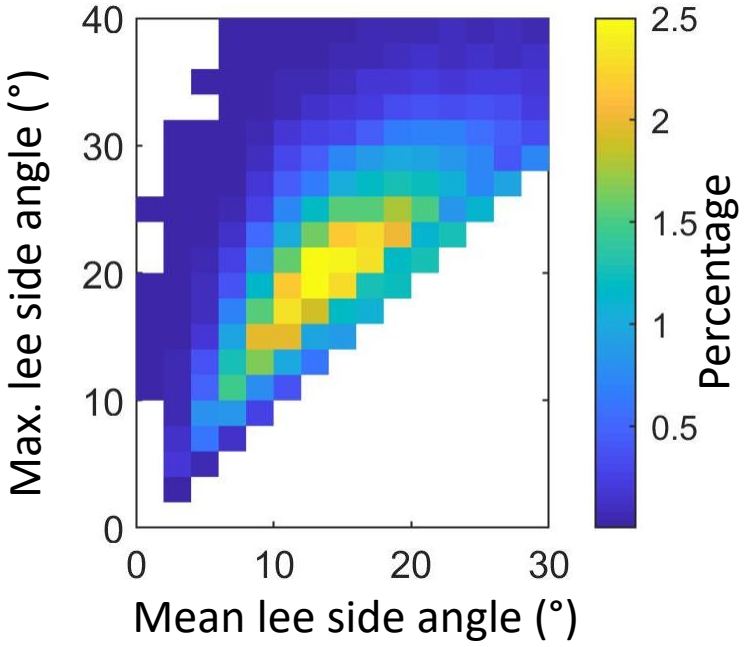
Lee side is not made of one straight line but has steeper and gentler slopes

Flow properties might vary depending on maximum slope (Lefebvre et al., 2016, Cisneros et al., 2021)

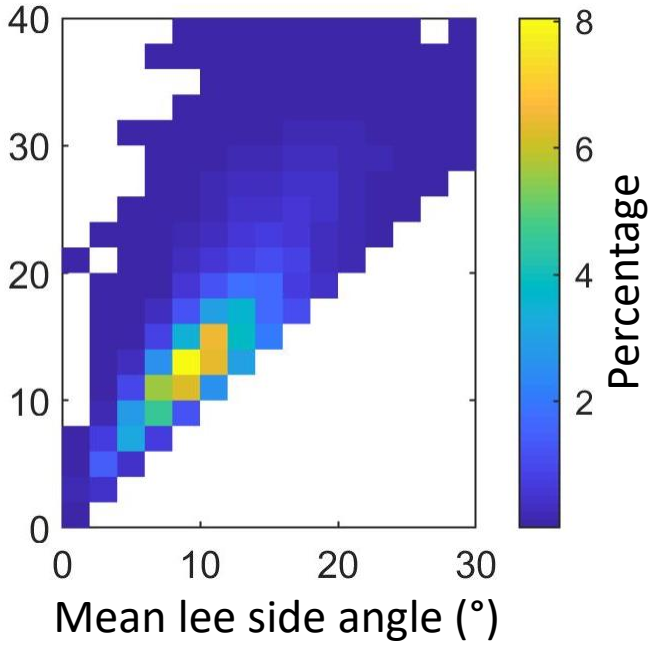
Maximum angle

There is a range of mean and maximum angles

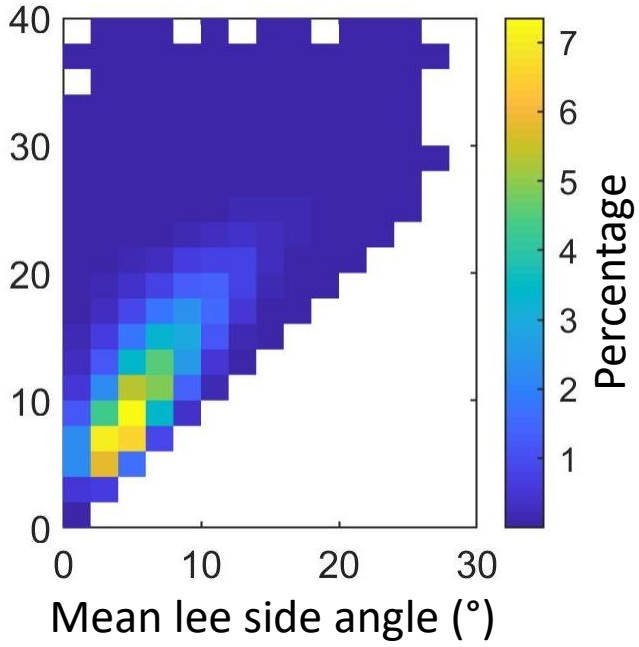
Mississippi River
Median mean angle 15°
Median max. angle 22°



Waal River
Median mean angle 10°
Median max. angle 14°



Weser Estuary
Median mean angle 5°
Median max. angle 11°

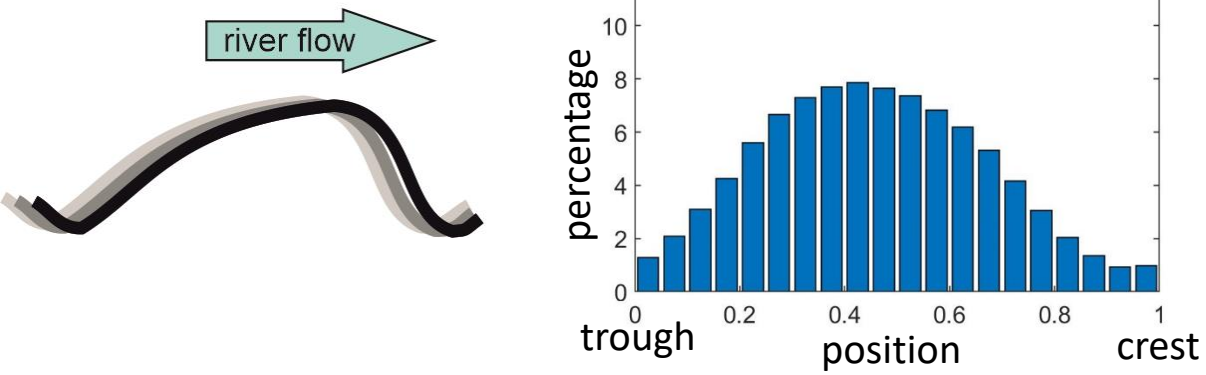


Steep face position differs for different type of dunes

The position of the maximum angle along the lee side varies depending on dune type

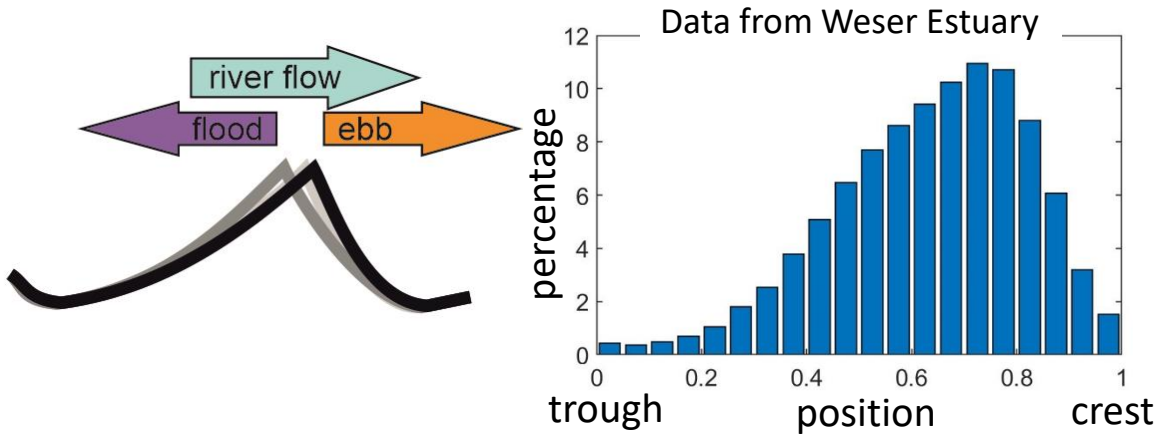
River dunes

Steepest slope close to the trough, rounded crest



Estuarine dunes

Steepest slope close to the crest, sharp crest

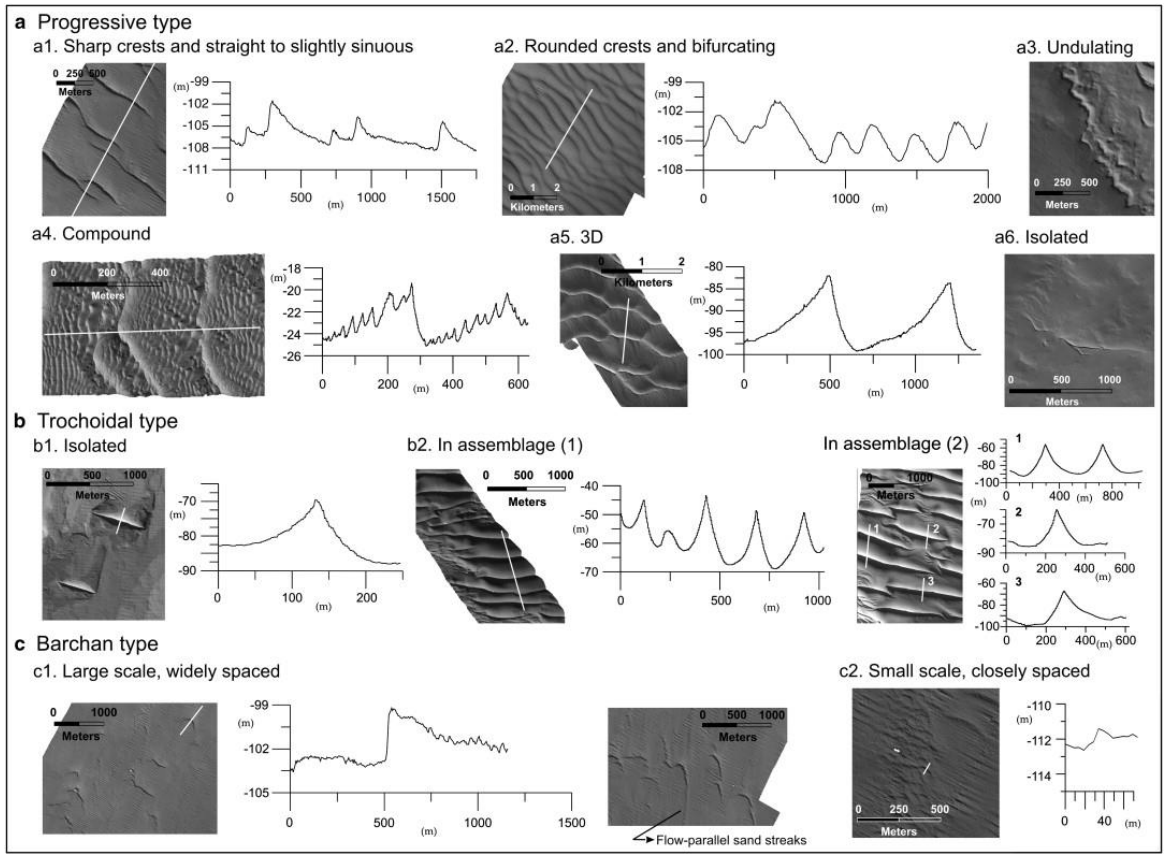


To know more about dunes in large rivers, check Cisneros, J., Best, J., van Dijk, T., de Almeida, R.P., Amsler, M., Boldt, J., Freitas, B., Galeazzi, C., Huizinga, R., Iannirubertо, M., Ma, H.B., Nittrouer, J.A., Oberg, K., Orfeo, O., Parsons, D., Szupiany, R., Wang, P., Zhang, Y.F. (2020). **Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape.** Nature Geoscience 13. https://doi.org/10.1038/s41561-019-0511-7

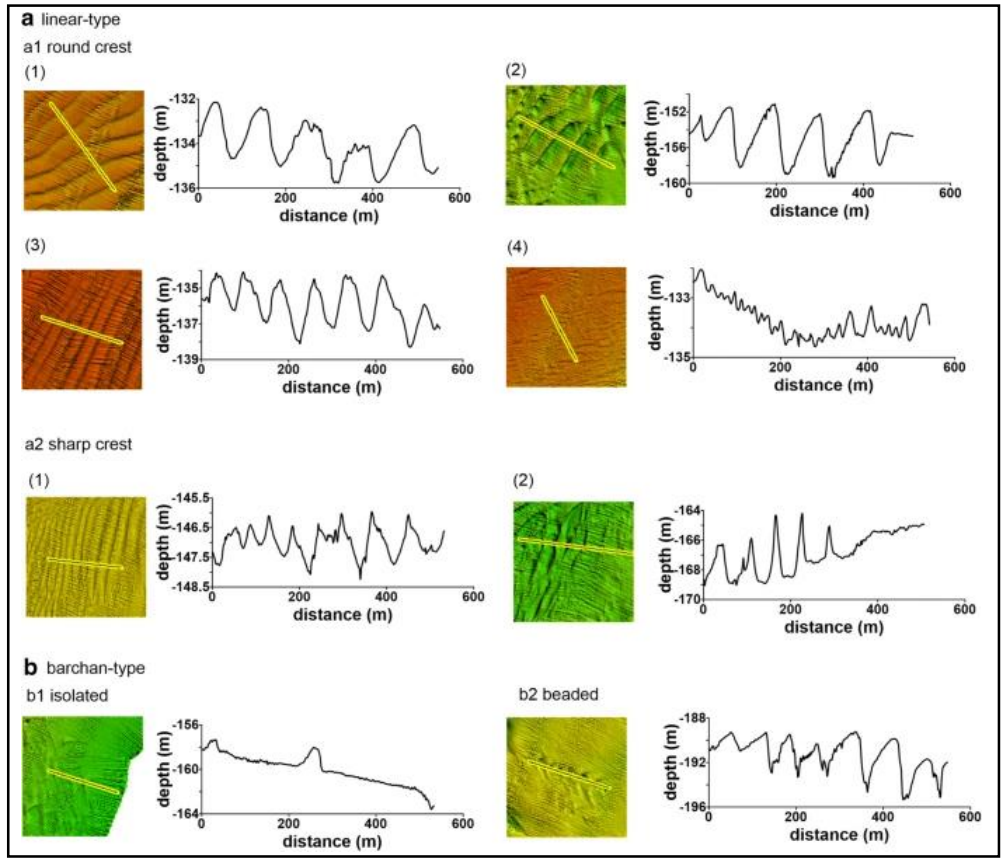
To know more about dunes in the Weser estuary, check Lefebvre, A., Herrling, G., Becker, M., Zorndt, A., Krämer, K., Winter, C. (2021). **Morphology of estuarine bedforms, Weser Estuary, Germany.** Earth Surface Processes and Landforms https://doi.org/10.1002/esp.5243

Marine dune morphology

In open marine environments, various morphology are found



Various marine dune types observed in the Irish Sea, Van Landeghem et al., 2009.



Various marine dune types observed near the shelf break of the northern South China Sea, Zhang et al., 2019

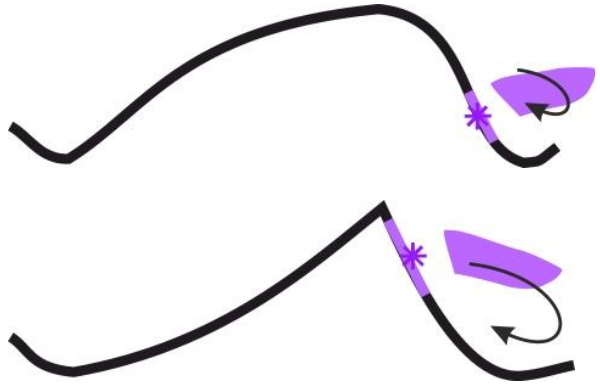
Question and hypothesis

Our question: What is the influence of the position of the steepest slope on flow properties above bedforms?

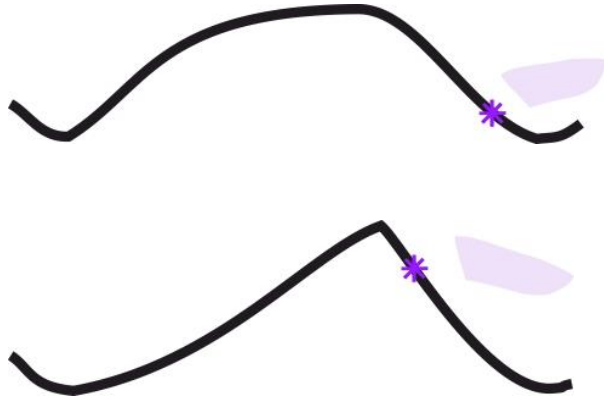
Our hypothesis:
the presence and size of flow separation and wake will depend on the angle and position of the steepest slope

Some of our thoughts before starting the experiments

Maximum angle > 15° close to the trough
Small flow separation over the steep face, strong turbulent wake extending upwards

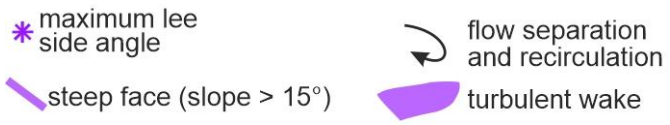


Maximum angle < 15° close to the trough
No flow separation, weak turbulent wake extending upwards



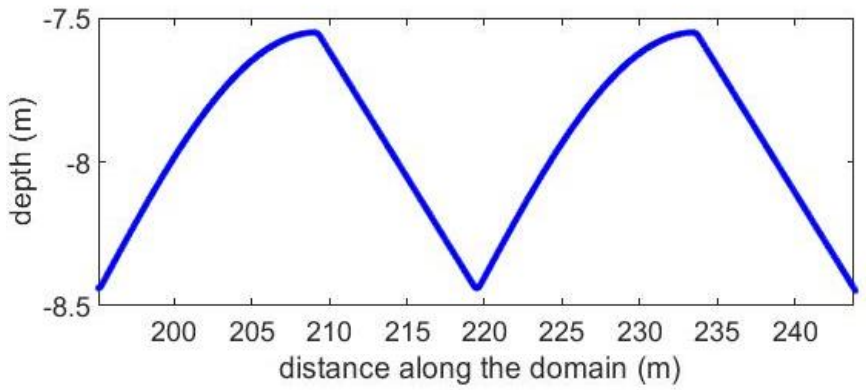
Maximum angle > 15° close to the crest
Flow separation over the steep face down to the trough, strong turbulent wake extending downwards

Maximum angle < 15° close to the crest
No flow separation, weak turbulent wake extending downwards



Method

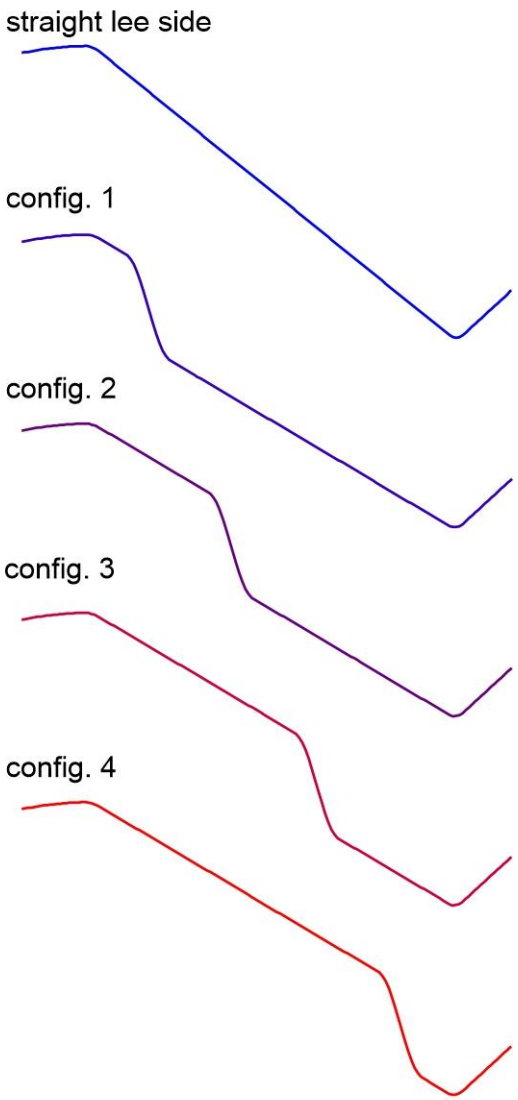
66 simulations with Delft3D-FLOW non-hydrostatic in 2DV (Lefebvre et al., 2014, 2016)



For all simulations: water depth h = 8 m; mean velocity u = 0.8 m s^{-1}; bedform height H = 0.89 m, 10 bedforms along the domain

Dune dimensions used for the numerical experiments

Straight lee side						
Mean lee side angle	5	10	15	20	25	30
Complex lee side – 4 configurations						
Mean lee side angle	5	10	15	20	25	
Maximum lee side angle	10, 15, 20, 25, 30	15, 20, 25, 30	20, 25, 30	25, 30	30	

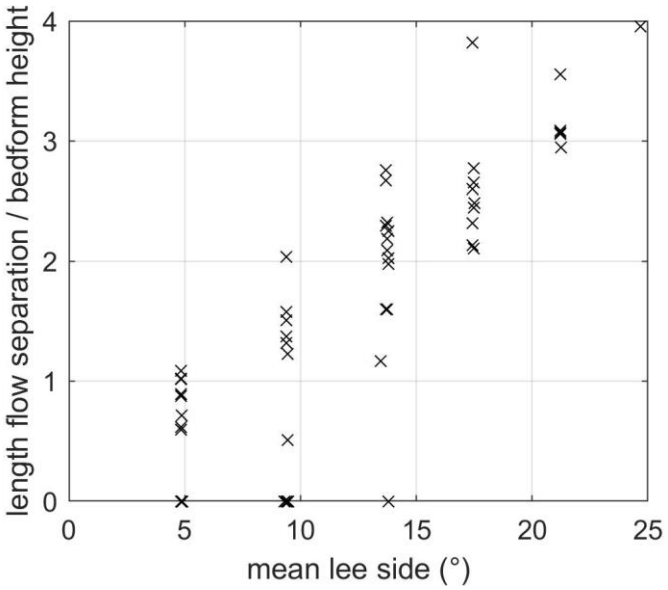


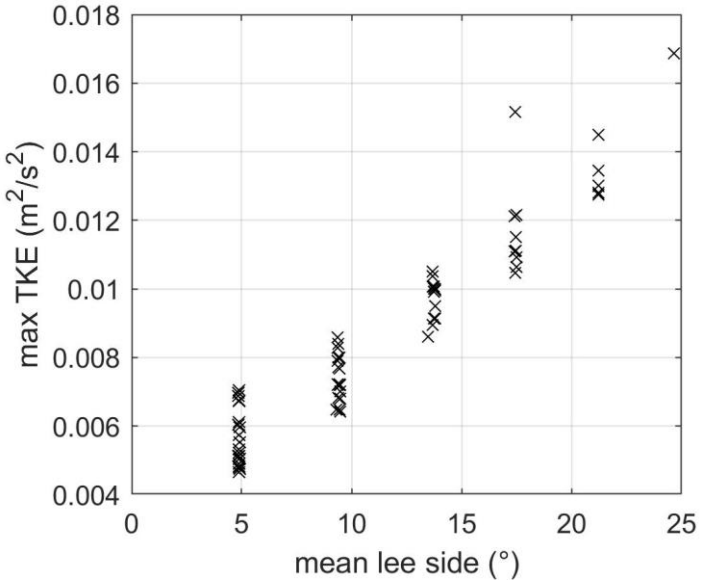
For each mean and maximum lee side angles: straight lee side + 4 configurations with a steep portion (height = 1/3 of dune height) with position going from close to the crest to close to the trough

5-points smoothing to avoid very sharp transitions between each segment

Overall results

length of the flow separation zone and mean and maximum turbulent kinetic energy (TKE) are increasing with increasing mean lee side angle

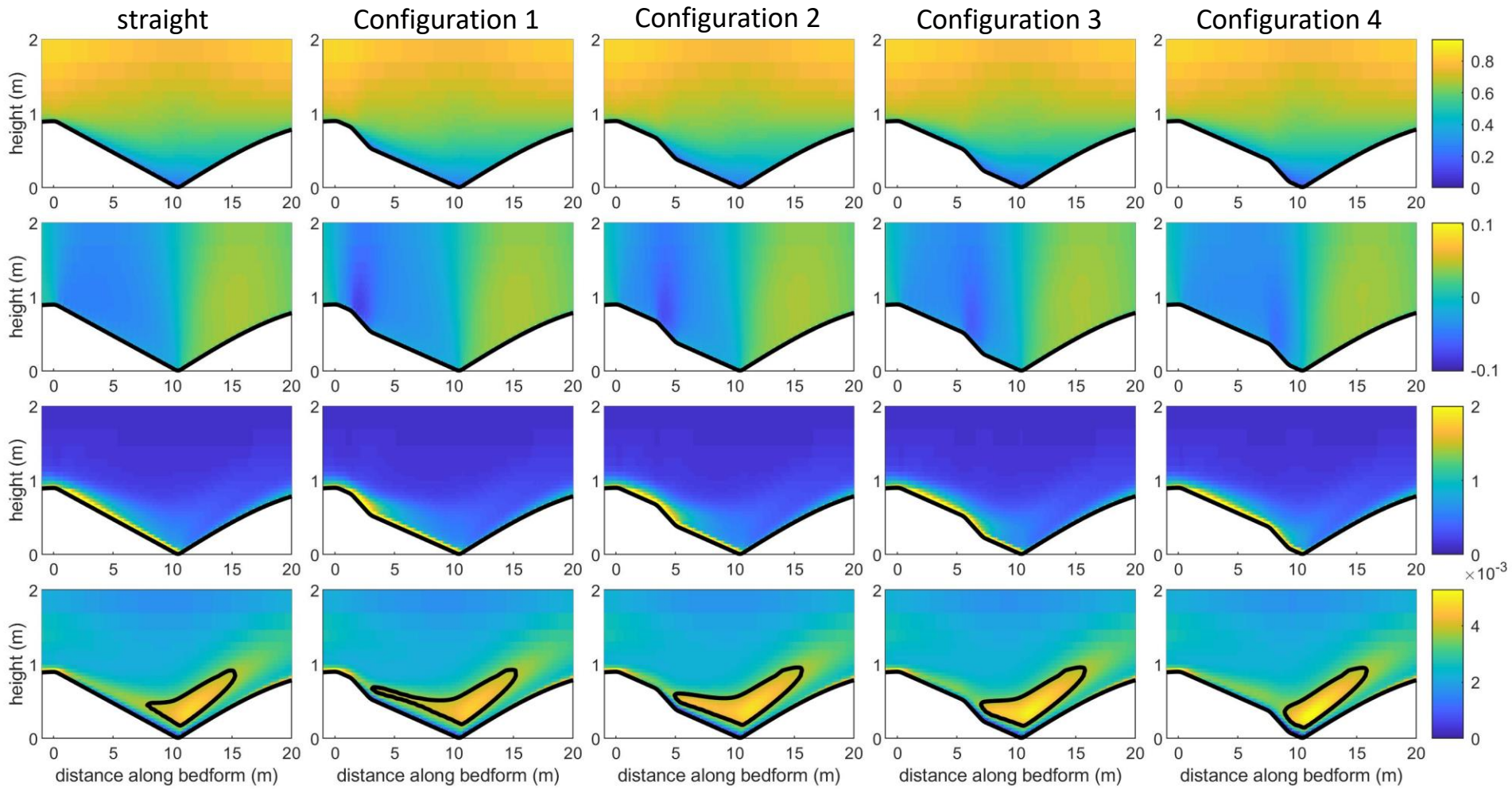




For more detail, need to make the difference between
Low-angle dunes – mean lee side less than 10°
Intermediate dues – mean lee side ca. 10° to 17°
High-angle dunes – mean lee side ca. more than 17°

Low-angle dunes with low maximum angle

Mean lee side angle 5°
Maximum angle 10°



Horizontal velocity (m/s)

Vertical velocity (m/s)

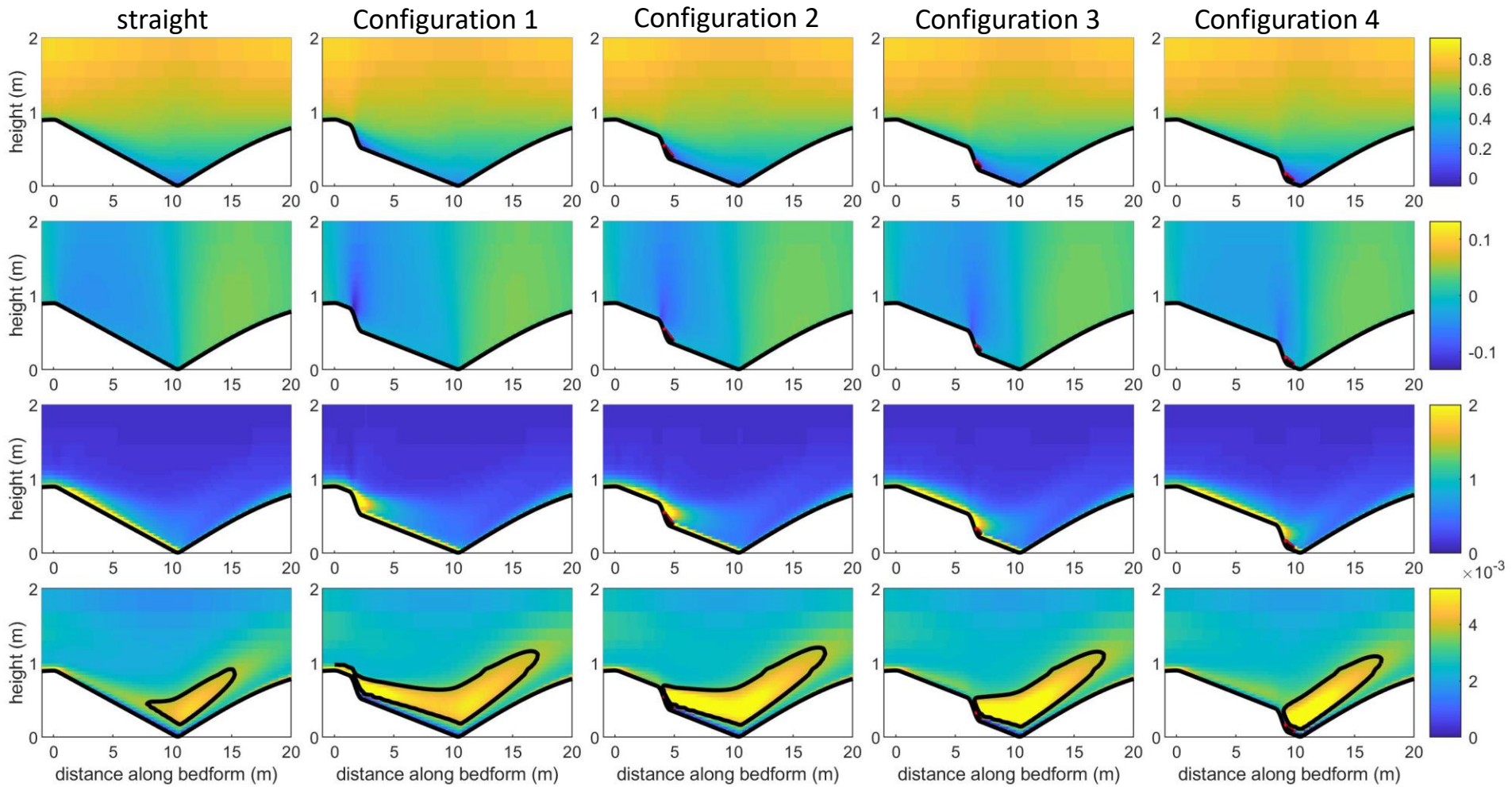
du/ dz (1/s) shear layer

turbulent kinetic energy (m^2/s^2)
In black, turbulent wake

No flow separation; turbulent wake is weakest but extends more for steep portions close to the crest and strongest but more contained for steep portions close to the trough.

Low-angle dunes with high maximum angle

Mean lee side angle 5°
Maximum angle 25°



Horizontal velocity (m/s)
In red, limit flow separation

Vertical velocity (m/s)

du/ dz (1/s)
shear layer

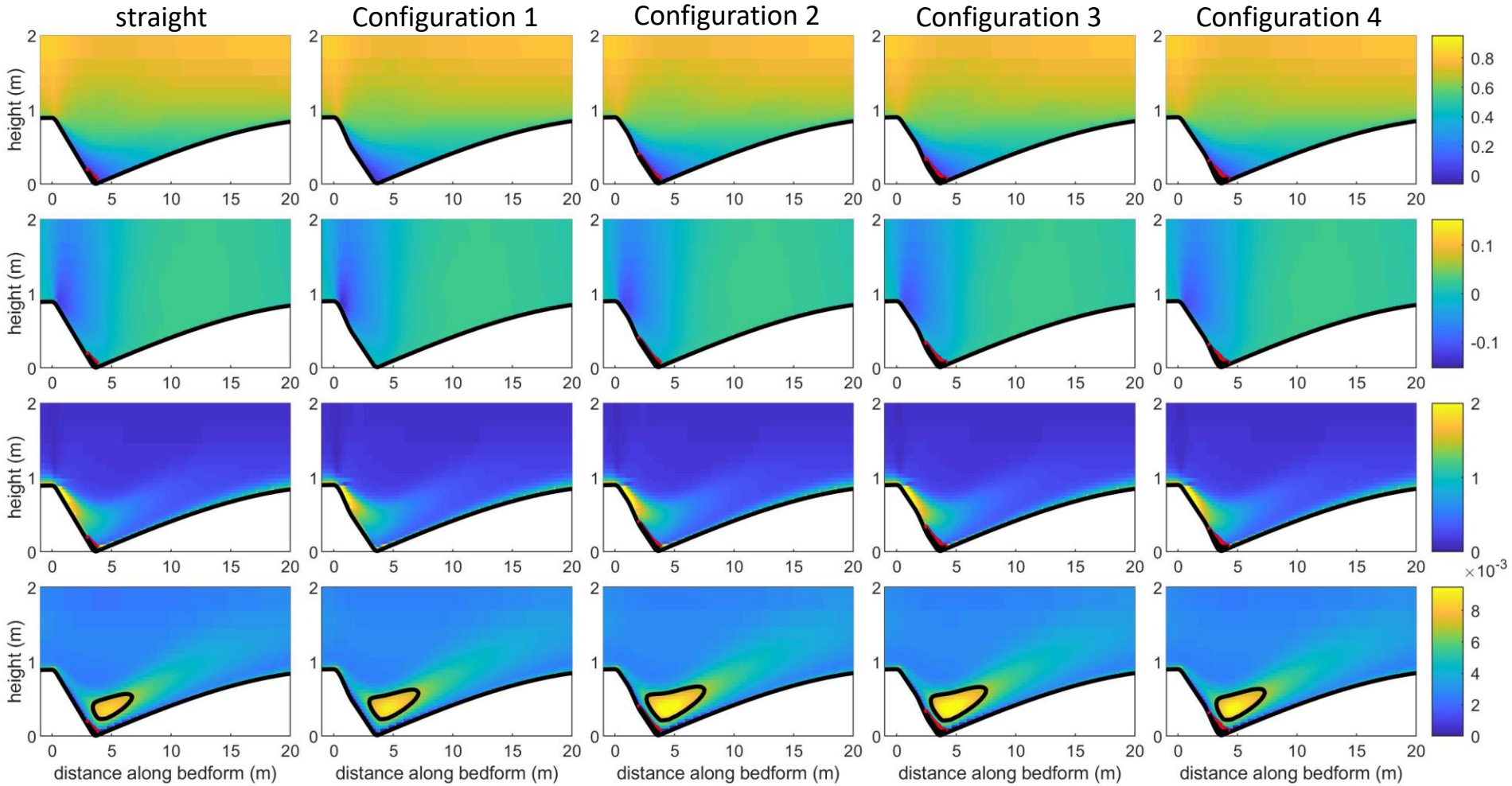
turbulent kinetic energy (m^2/s^2)
In black, turbulent wake

Small flow separation forms, except if the steep portion is close to the crest;

Same wake variations as with low maximum angle

Intermediate-angle dunes

Mean lee side angle 15°
Maximum angle 20°



Horizontal velocity (m/s)
In red, limit flow separation

Vertical velocity (m/s)

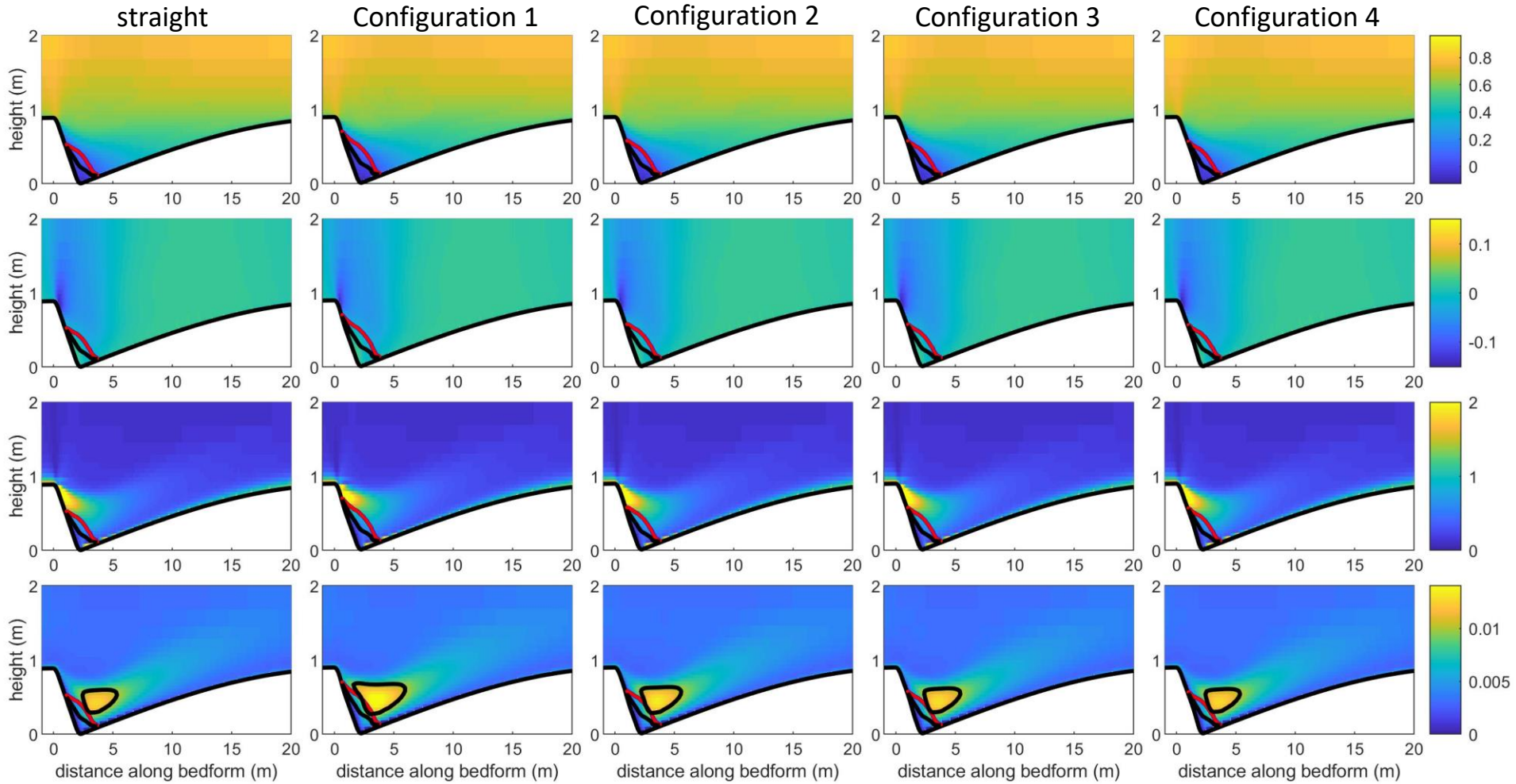
du/ dz (1/s)
shear layer

turbulent kinetic energy (m^2/s^2)
In black, turbulent wake

The flow does not separate at the brink point, but close to the trough, no matter the presence or position of the maximum slope. The wake is strongest and more extended for Configuration 2.

High-angle dunes

Mean lee side angle 25°
Maximum angle 30°



Horizontal velocity (m/s)
In red, limit flow separation

Vertical velocity (m/s)

du/ dz (1/s)
shear layer

turbulent kinetic energy (m^2/s^2)
In black, turbulent wake

The flow separates over the maximum slope or higher, and extends over the trough to the next stoss side. The wake is strongest and largest for steep portions close to the crest and lowest and more contained for steep portions close to the trough

Summary

What is the influence of the position of the steepest slope on flow properties above bedforms?

In depends on the mean lee side angle. We can differentiate 3 types of dunes

Low-angle dunes, with mean lee side less than ca. 10°
➔ No flow separation or very small if maximum angle > 25° close to through
➔ Turbulent wake is weak, strongest and more contained as maximum slope is steeper and situated closer to the trough

Intermediate-angle dunes, with mean lee side around 15° (10 to 17°)
➔ RANS model may not be appropriate to study such bedforms due to flow intermittency
➔ Need of lab experiments or LES modelling

High-angle dunes, with mean lee side of more than ca. 17°
➔ Flow separation is longer if steep face is close to the crest
➔ Turbulent wake is strong, strongest and more extended as maximum slope is steeper and situated closer to the crest

Implications

Results have implications for bedform roughness and sediment transport:

- **bedform roughness** is linked to turbulent wake. The wake size and strength vary depending on mean and maximum lee side angle, and steep face position (note difference between high and low-angle dunes)

- **sediment transport** will be affected by the presence and size of flow separation zone which may carry sediment upstream. The flow separation zone presence and size vary depending on mean and maximum lee side angle, and steep face position

We recommend to distinguish 3 types of dunes:

low-angle dunes, intermediate angle dune and high-angle dunes.

It is not only the mean and maximum angle, but also the **shape** which matters!

The influence of dune lee side shape on flow above bedforms

Alice Lefebvre

MARUM – Center for Marine Environmental Sciences

University of Bremen, Germany

alefebvre@marum.de

@DrAliceLefebvre

Julia Cisneros

Texas A&M University

University of Texas at Austin

Texas Tech University

jcisneros1024@gmail.com

@Juliamorphology

Universität Bremen

marum Center for Marine Environmental Sciences