3RD INTERNATIONAL WORKSHOP ON

Waves, Storm Surges, and Coastal Hazards

UNIVERSITY OF NOTRE DAME

Wave-by-wave forecasting: What do we need?

Alexis MERIGAUD and Paolino TONA

ifp Energies nouvelles

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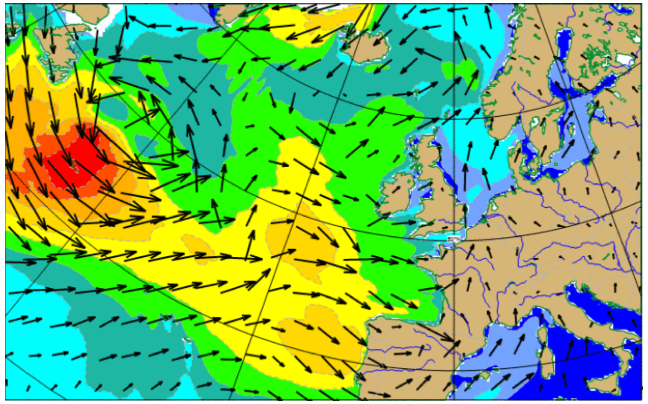
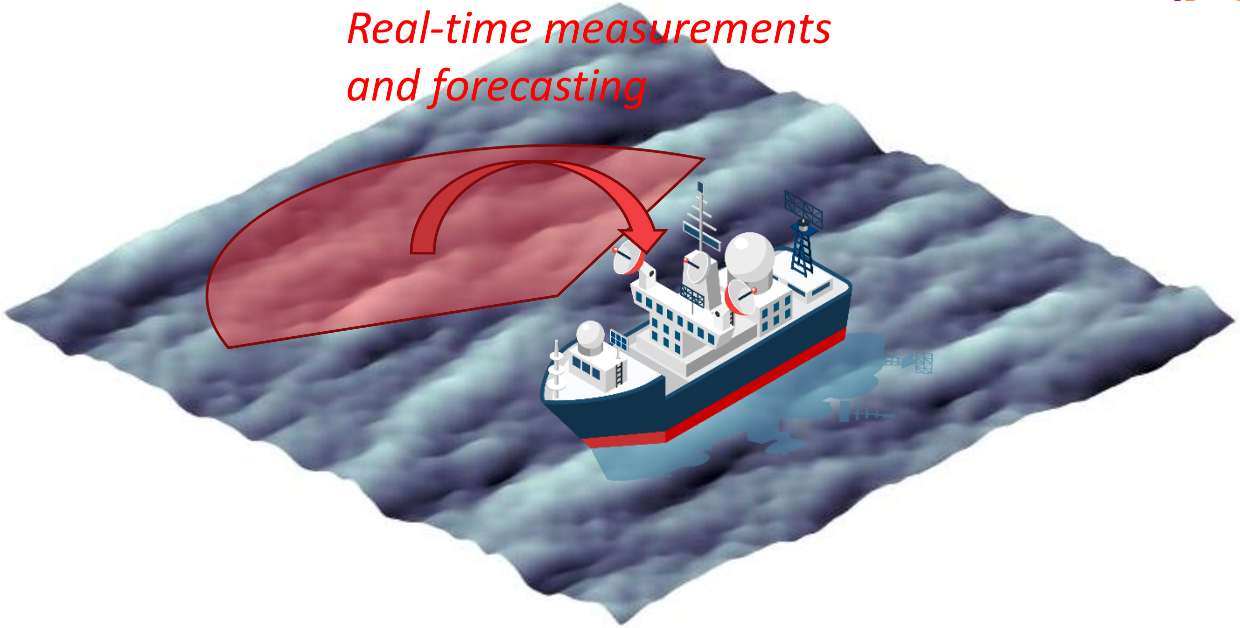
Wave-by-wave forecasting



Source: ECMWF

Met-ocean forecasts ($T > 1$h)



Wave-by-wave forecasts ($T \approx 1$ min)

-> Model-predictive control:

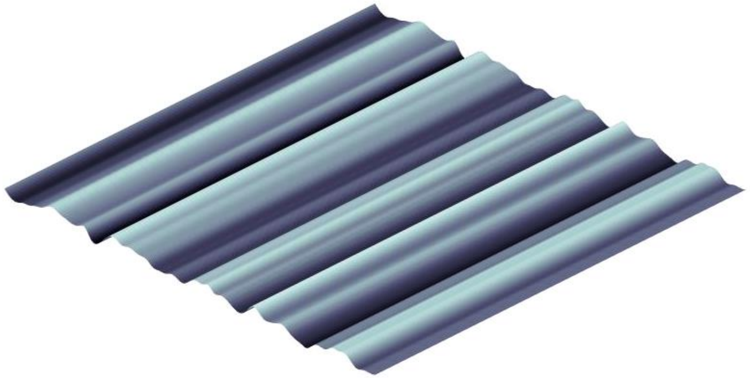
- For motion compensation, dynamic positioning, ship stabilisation, FOWT control, wave energy device control, etc.

-> Decision support system:

- Through quiescent wave run or dangerous wave train prediction,
- For lifting and drilling operations, transfers and ship-to-ship operations, ROV launch and recovery, helicopter landing, etc.

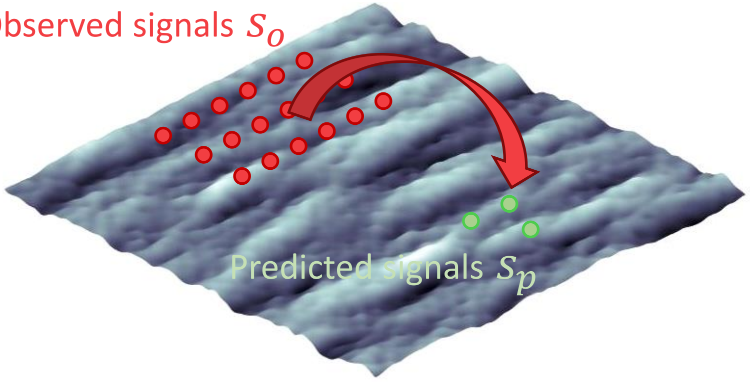
Wave-by-wave forecasting paradigms

2D

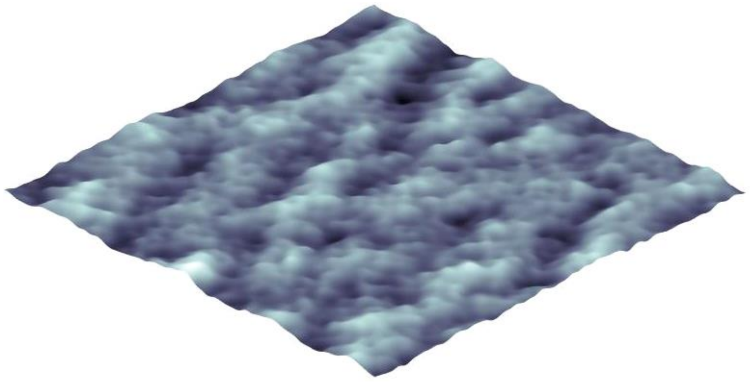


Two-dimensional waves (e.g. wave flume in the lab)

3D



Long-crested sea (focused swell)



Short-crested sea (wind waves)

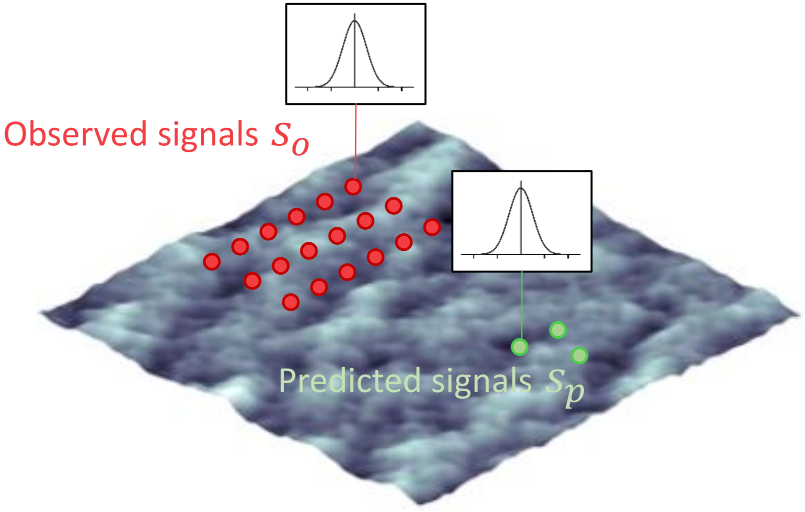
Measured values → Forecasting method or model → Predicted values

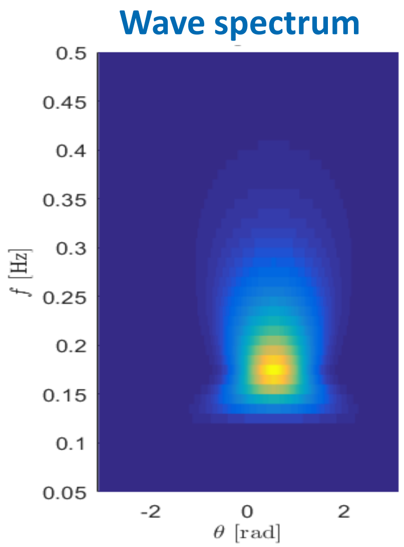
Deterministic point of view

Stochastic point of view

A stochastic view on wave forecasting

Classical Gaussian wave description
Over our small scales in space and time, the wave elevation is a homogeneous, stationary, Gaussian random field





Wiener-Khinchine relation

$$\begin{pmatrix} s_o \\ s_p \end{pmatrix} \sim N\left(0, \begin{pmatrix} R_{oo} & R_{op} \\ R_{po} & R_{pp} \end{pmatrix}\right)$$

$$P = R_{po} R_{oo}^{-1}$$

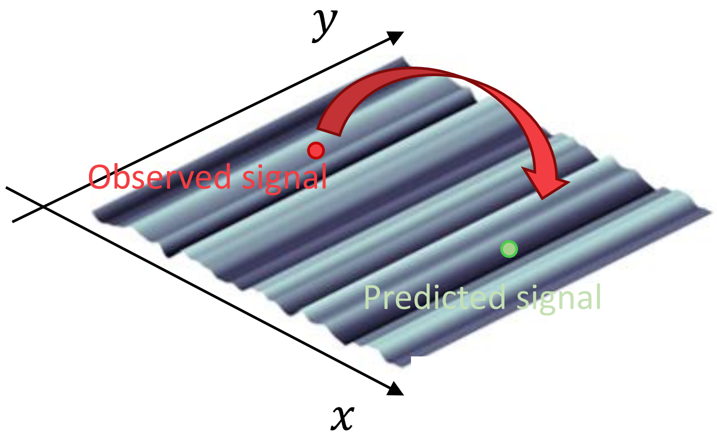
Optimal prediction $\tilde{s}_p = P s_o$
with error $\epsilon = s_p - \tilde{s}_p$

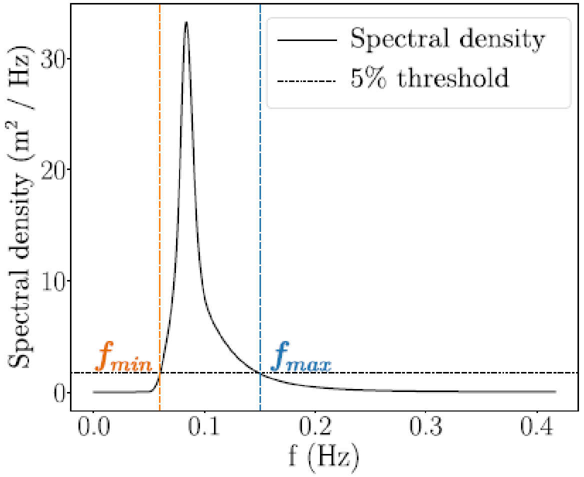
$$R_{\epsilon\epsilon} = R_{pp}^{-1} - R_{po} R_{oo}^{-1} R_{op}$$

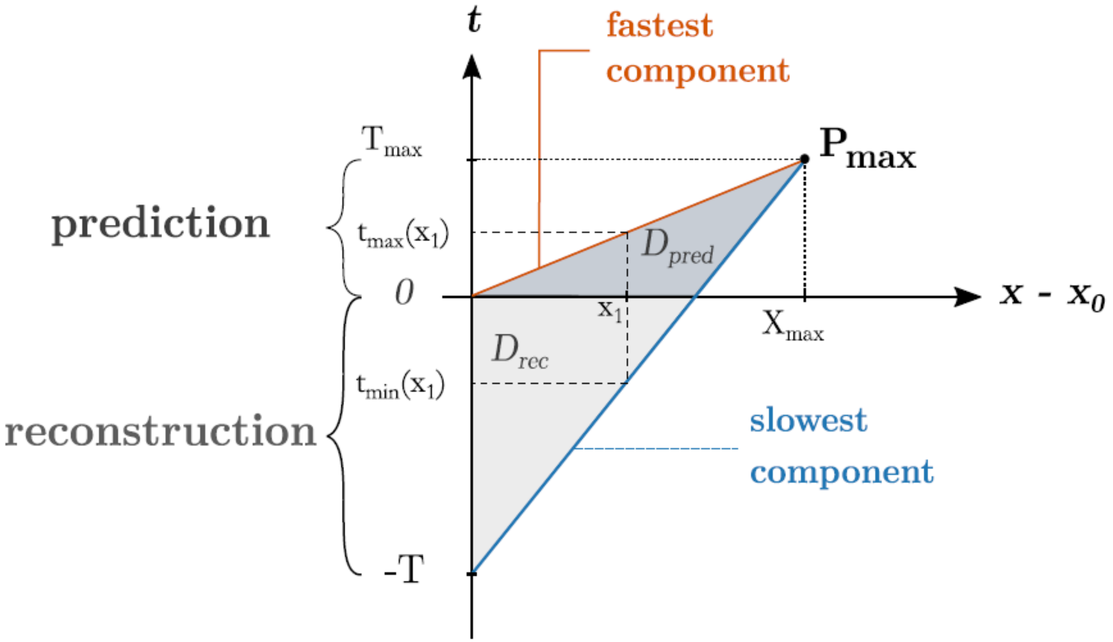
Optimal prediction error characterisation

Mérigaud and Ringwood, IEEE JOE, 2018
Mérigaud and Tona, OMAE 2022

Deterministic prediction zone in 2D

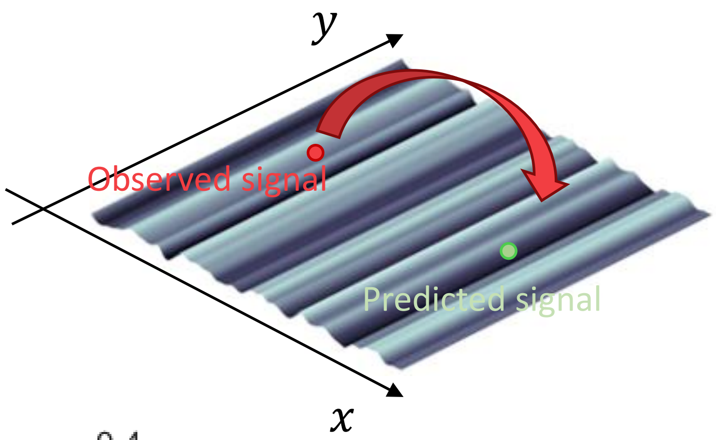


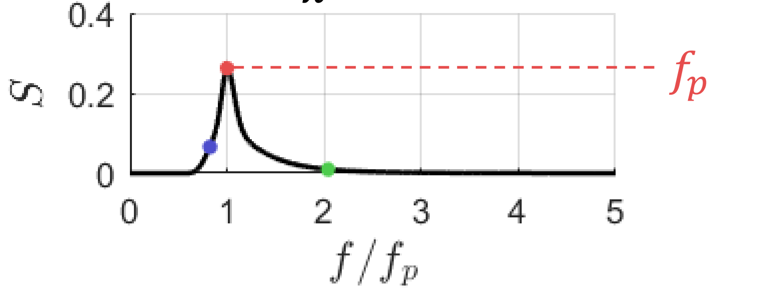


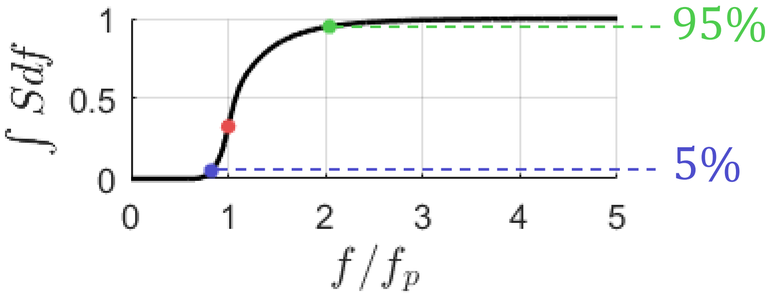


Huchet et al, Ocean Eng. 2023

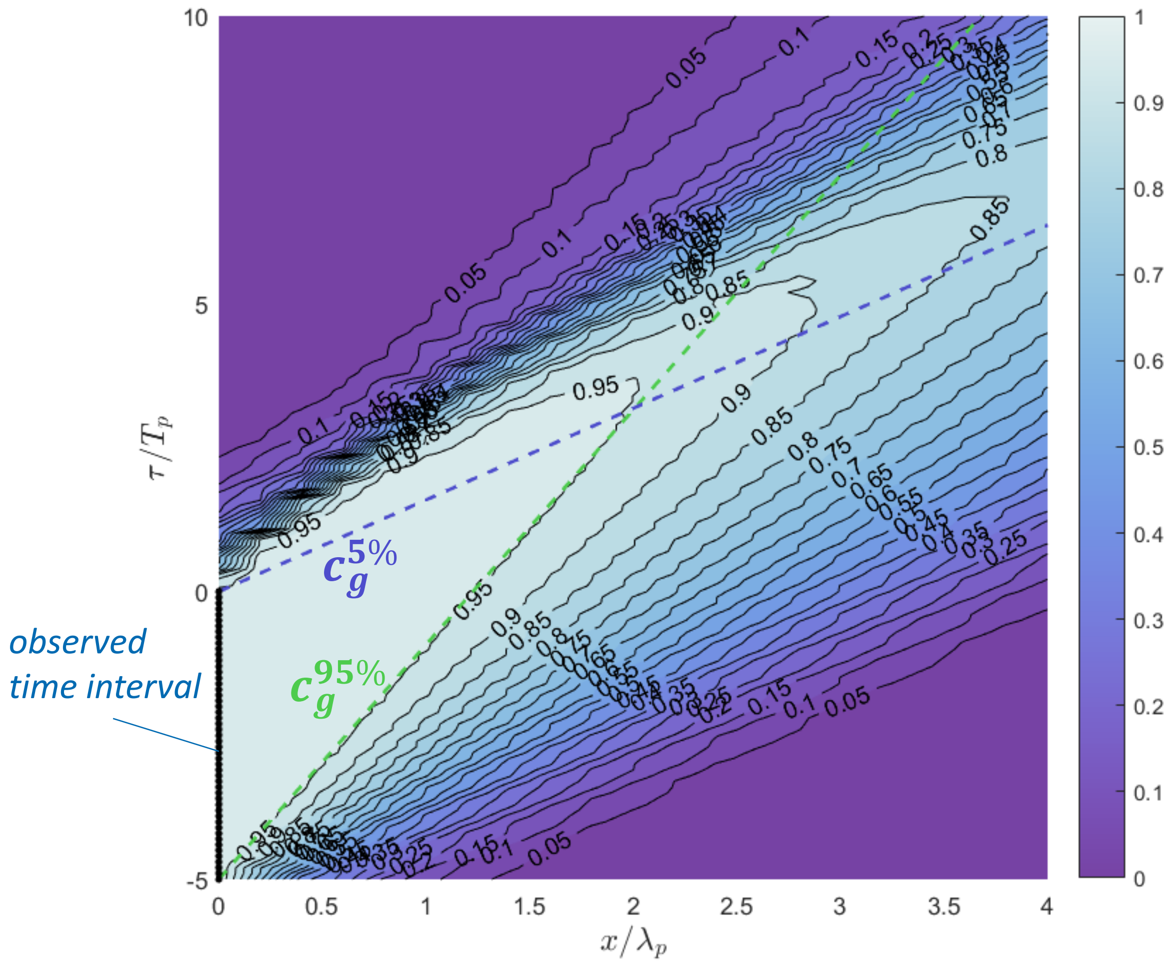
Probabilistic prediction zone in 2D



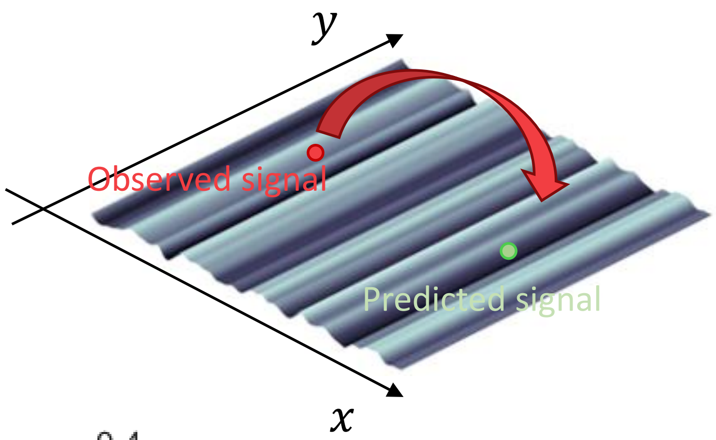


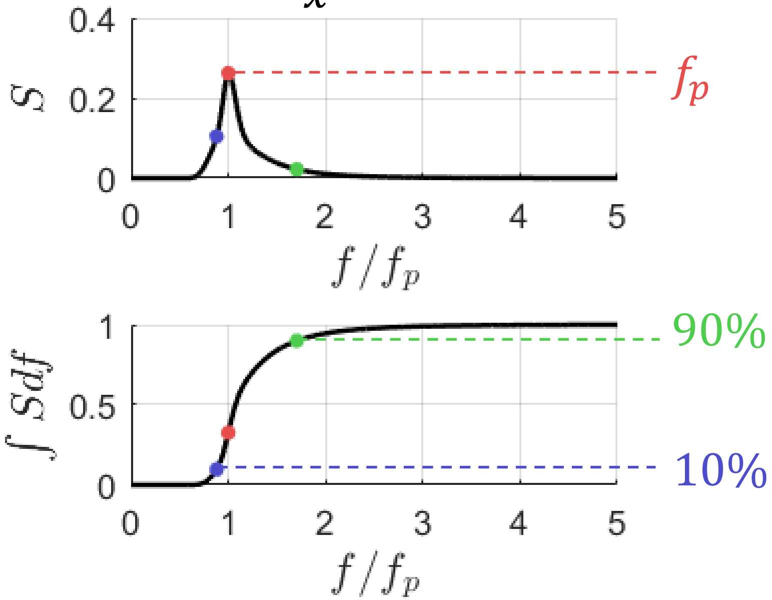


Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$



Probabilistic prediction zone in 2D





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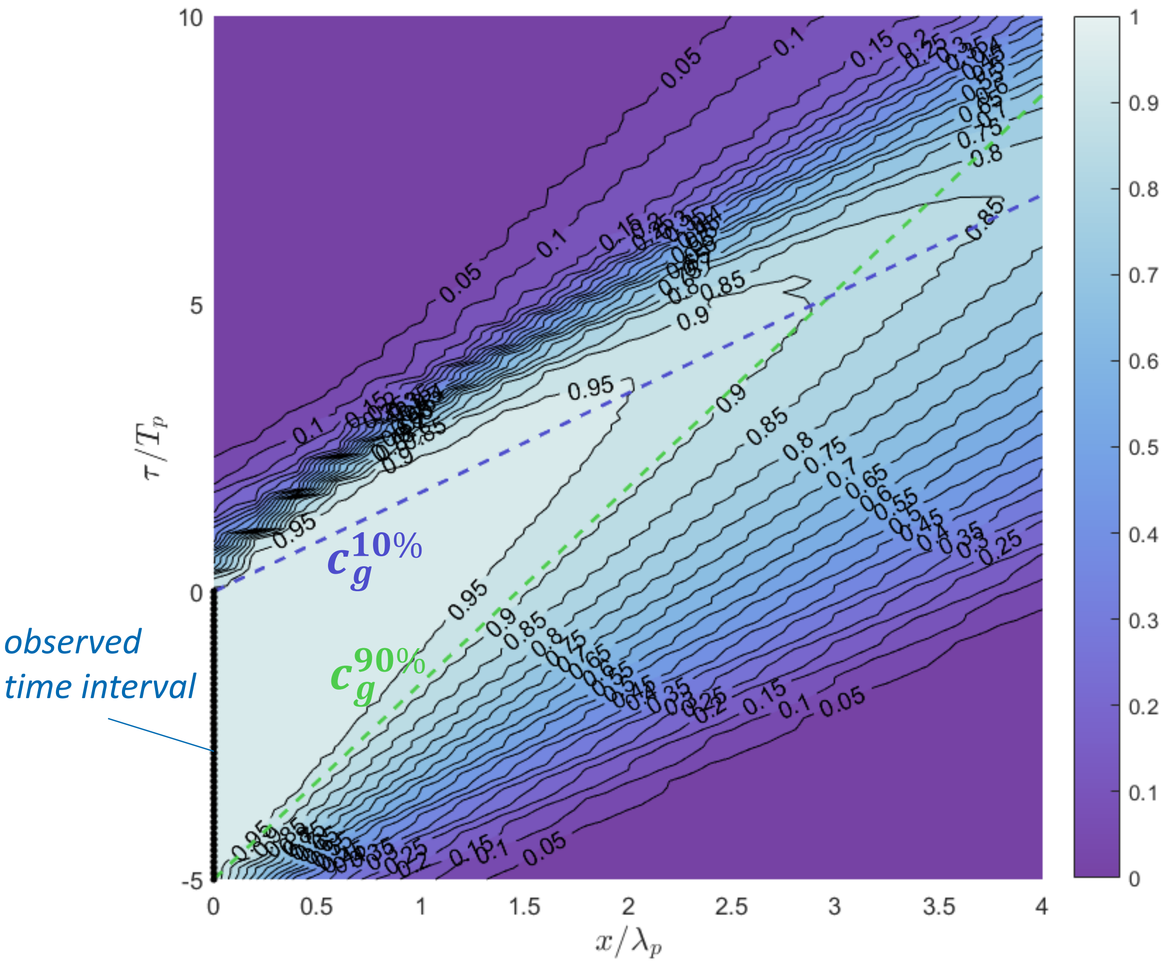
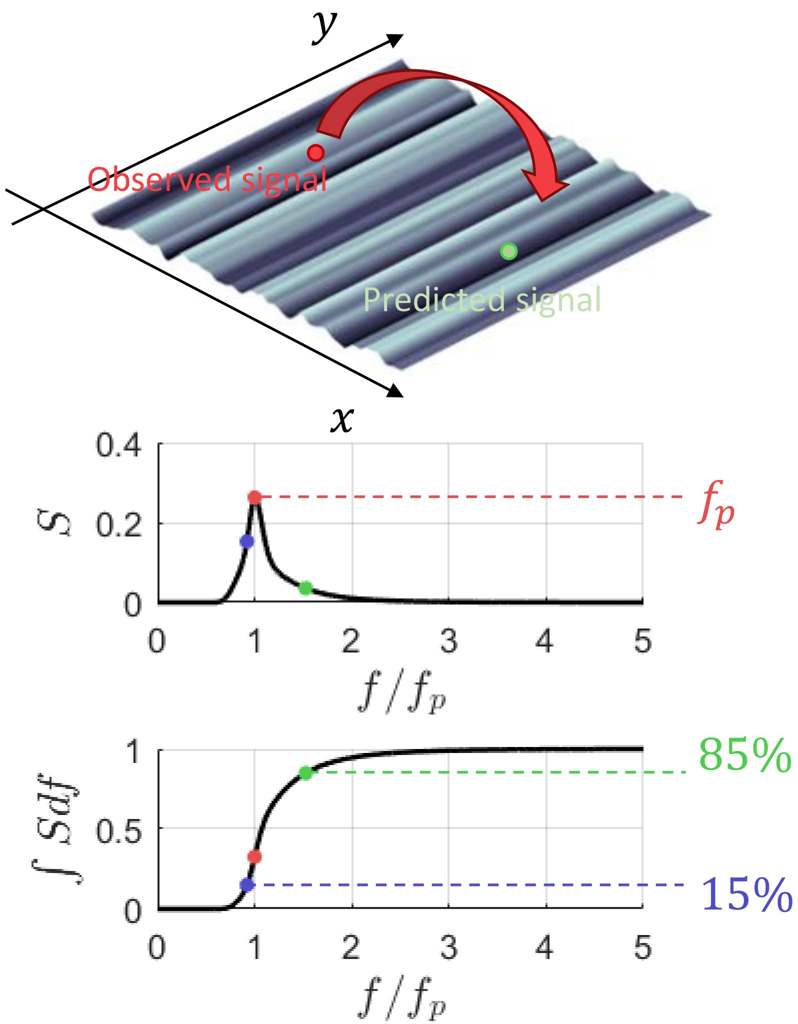


Probabilistic prediction zone in 2D



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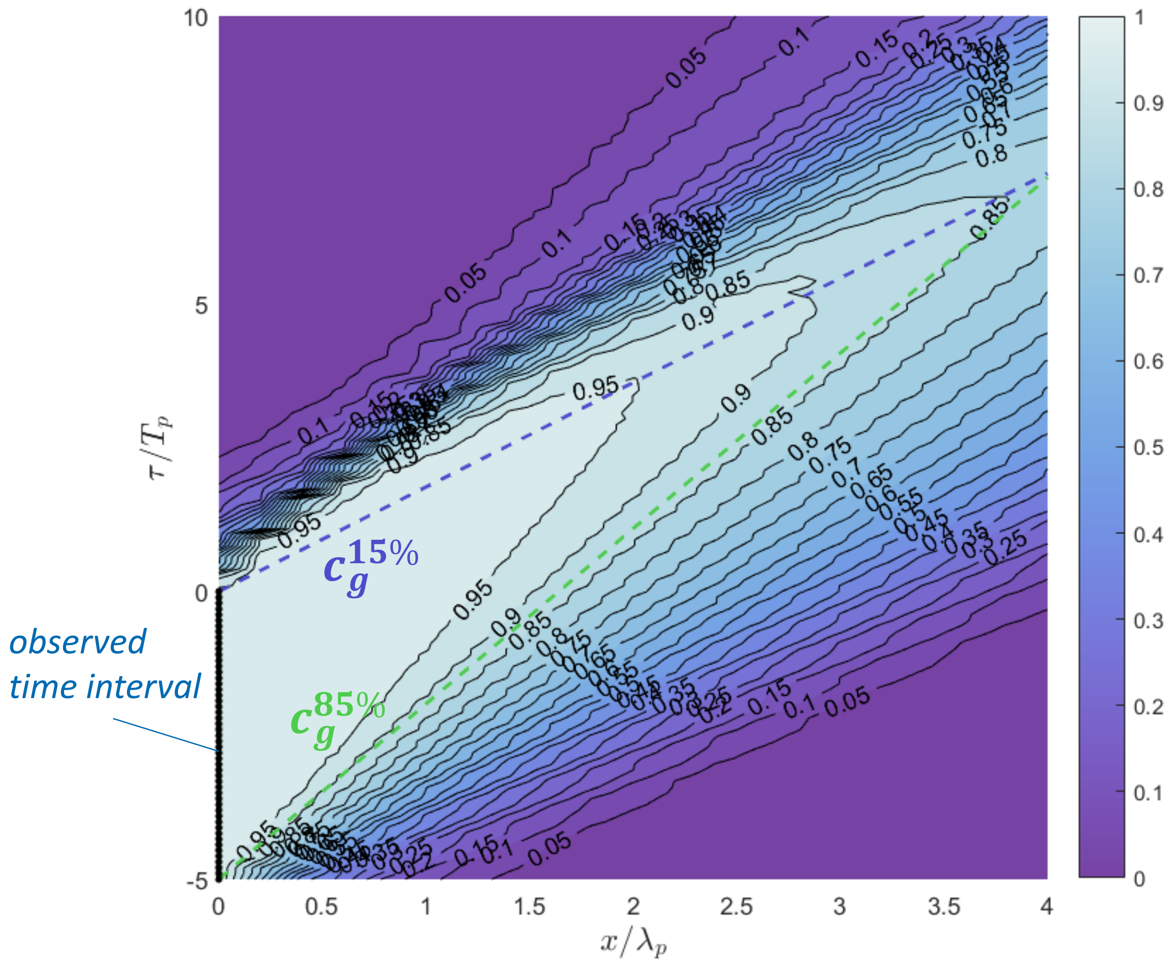
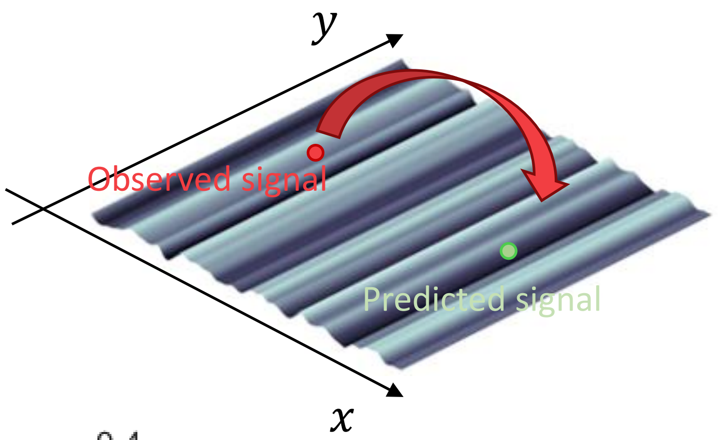
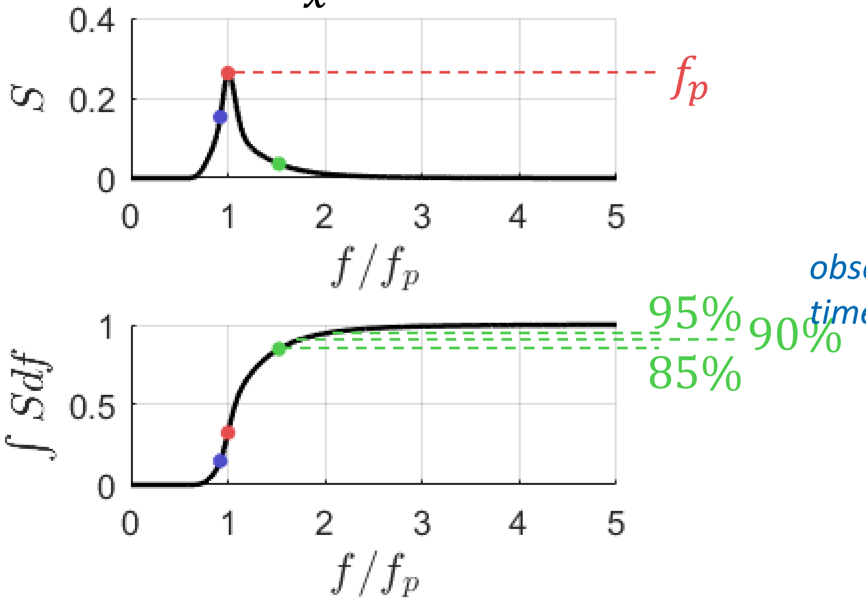
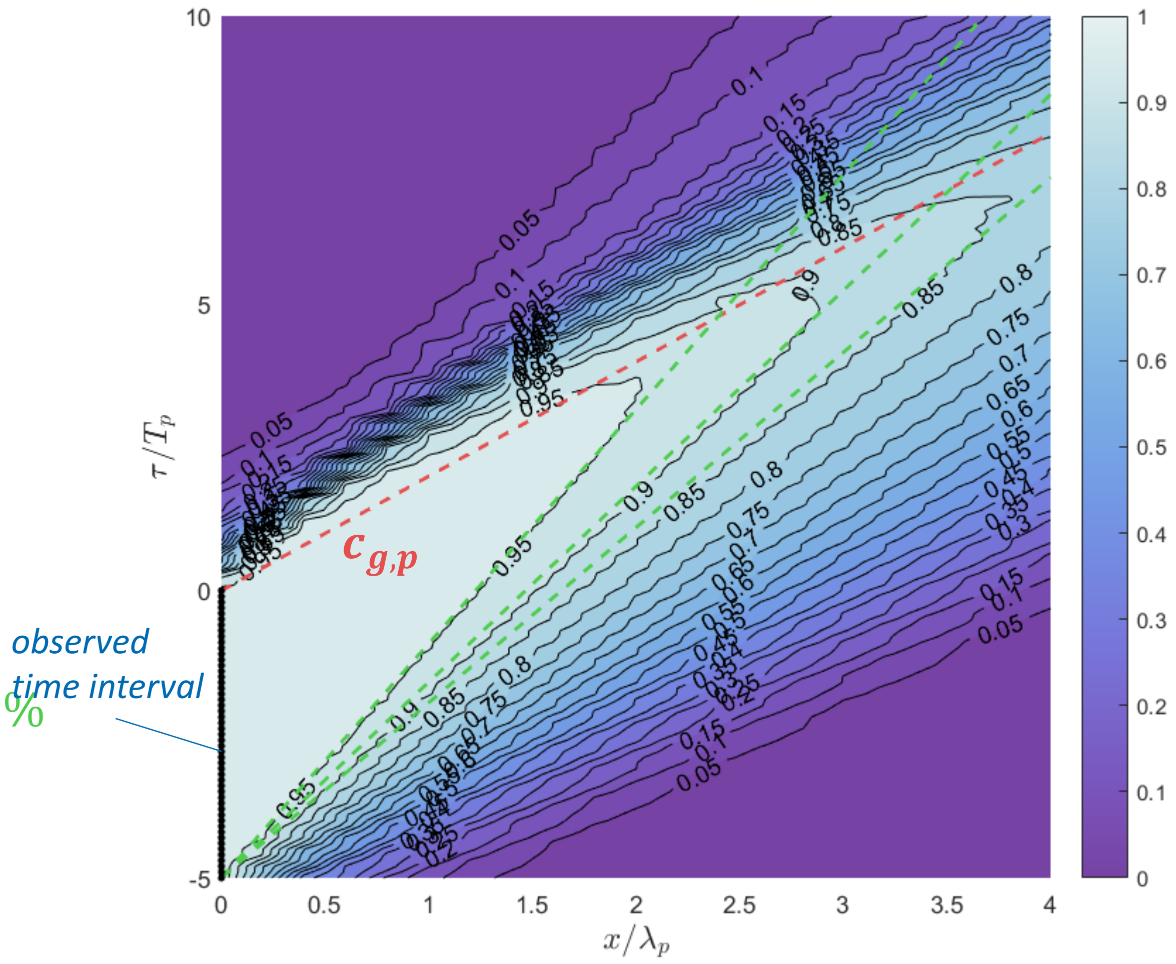


Probabilistic prediction zone in 2D



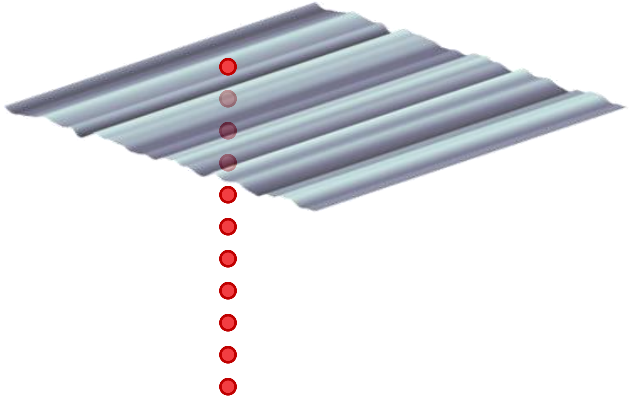


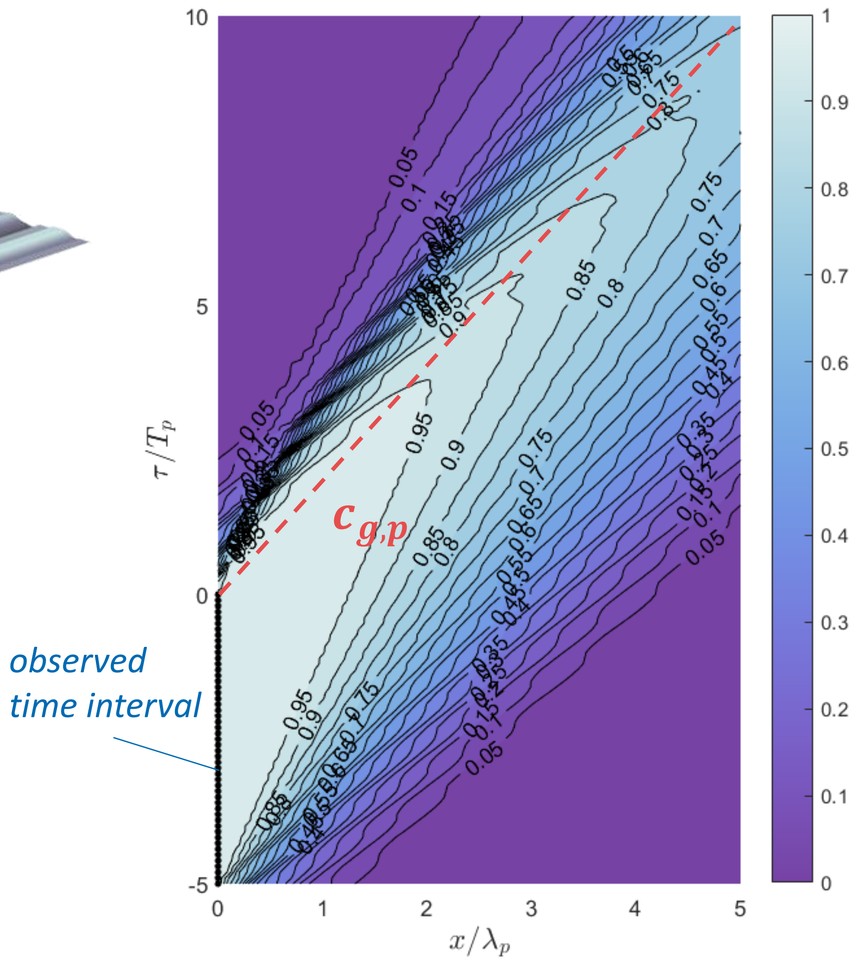
Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$



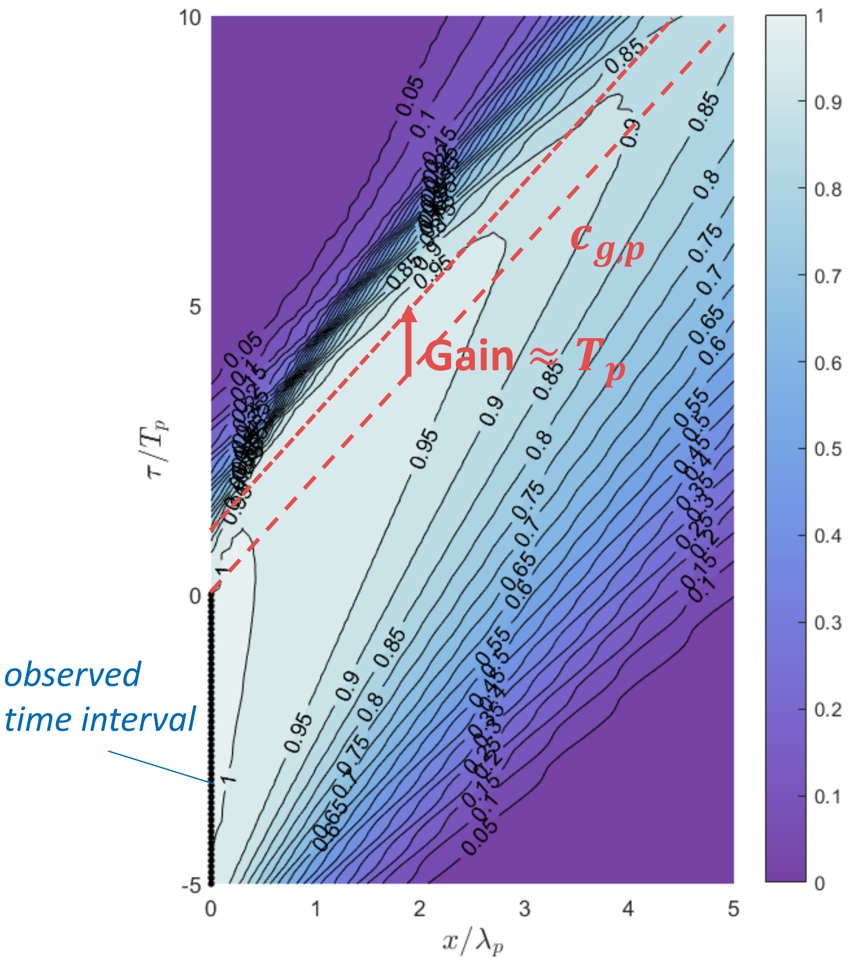
What about water column measurements ?

Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$





Measuring η only



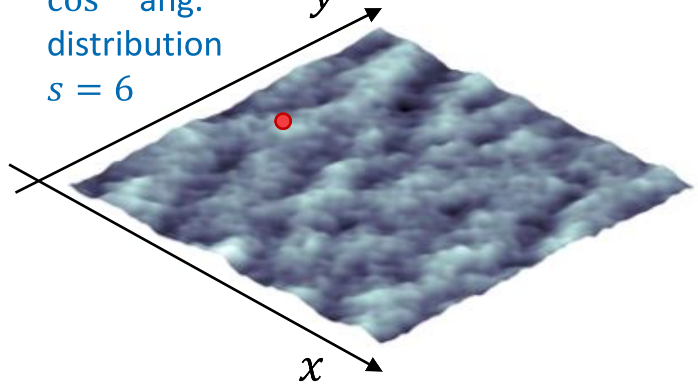
Measuring η + the pressure along the water column

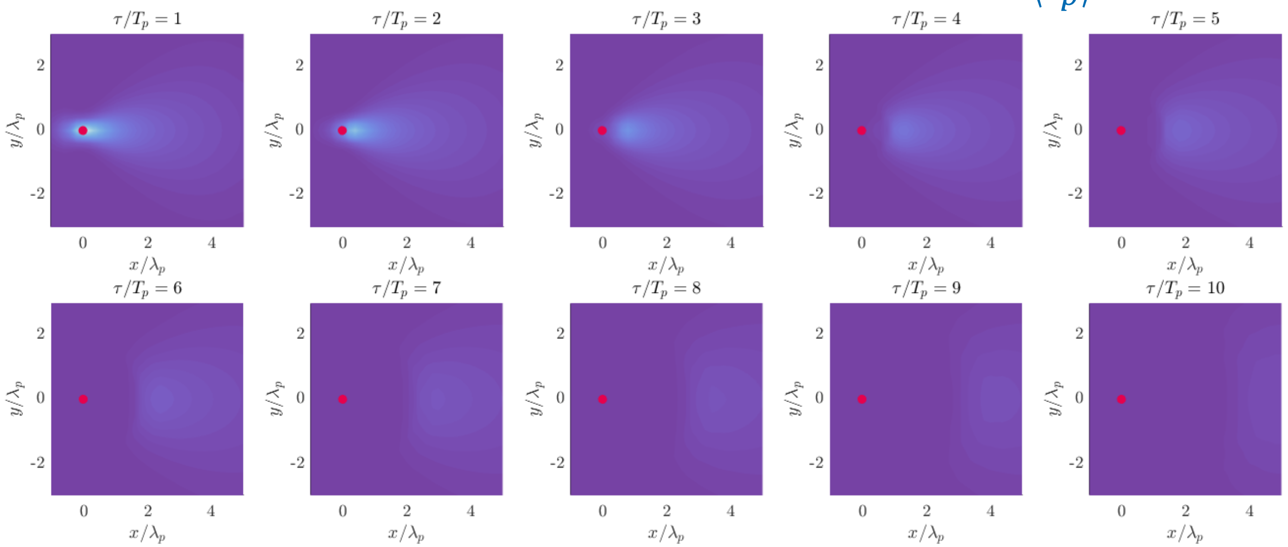
Probabilistic prediction zone in 3D

Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$

Short-crested wind sea

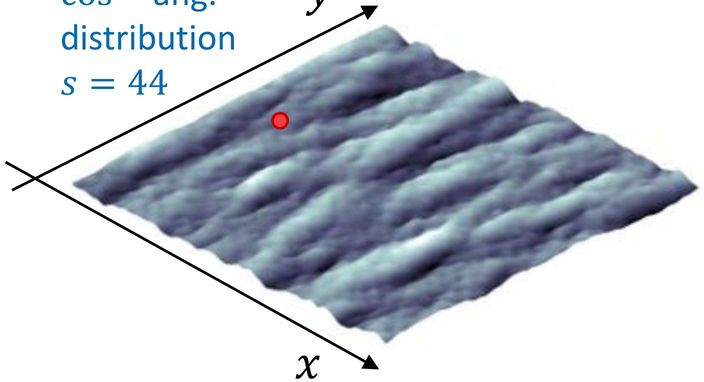
$\cos^{2s}$ ang. distribution $s = 6$

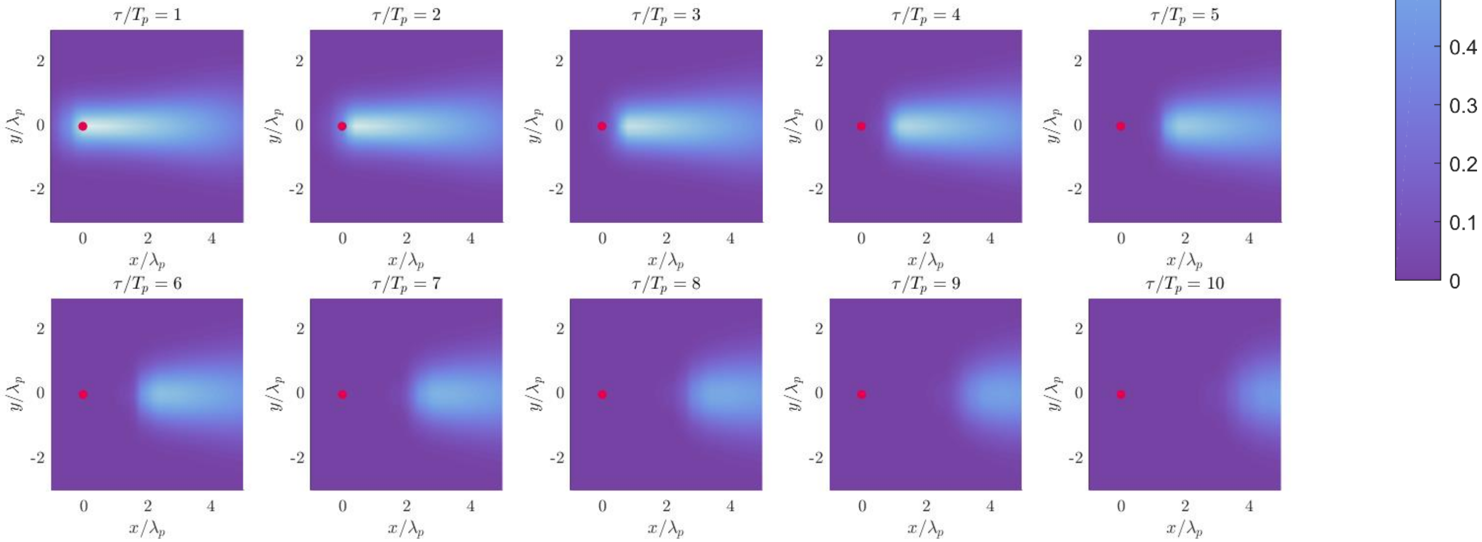




Long-crested swell

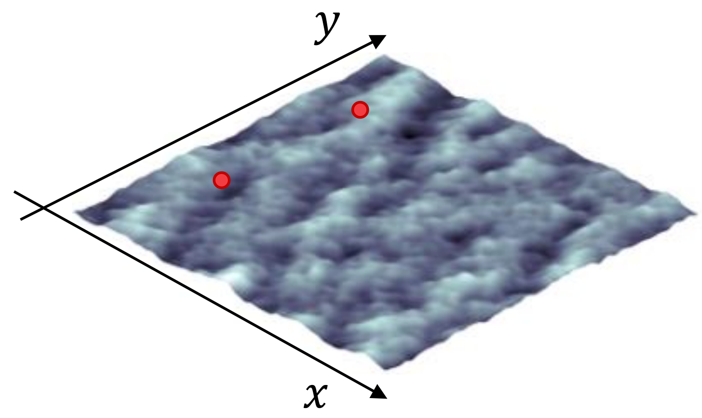
$\cos^{2s}$ ang. distribution $s = 44$



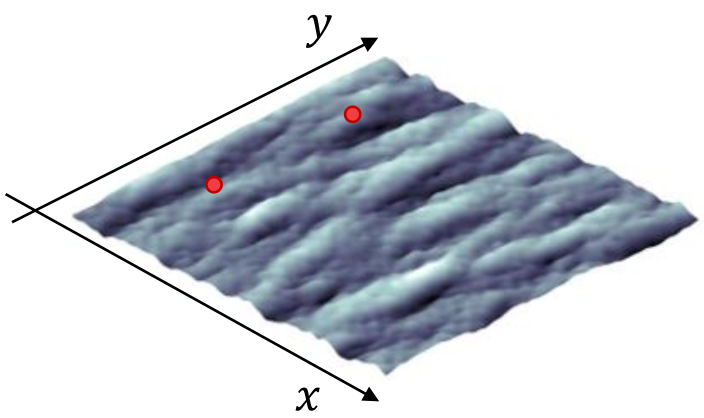


Probabilistic prediction zone in 3D

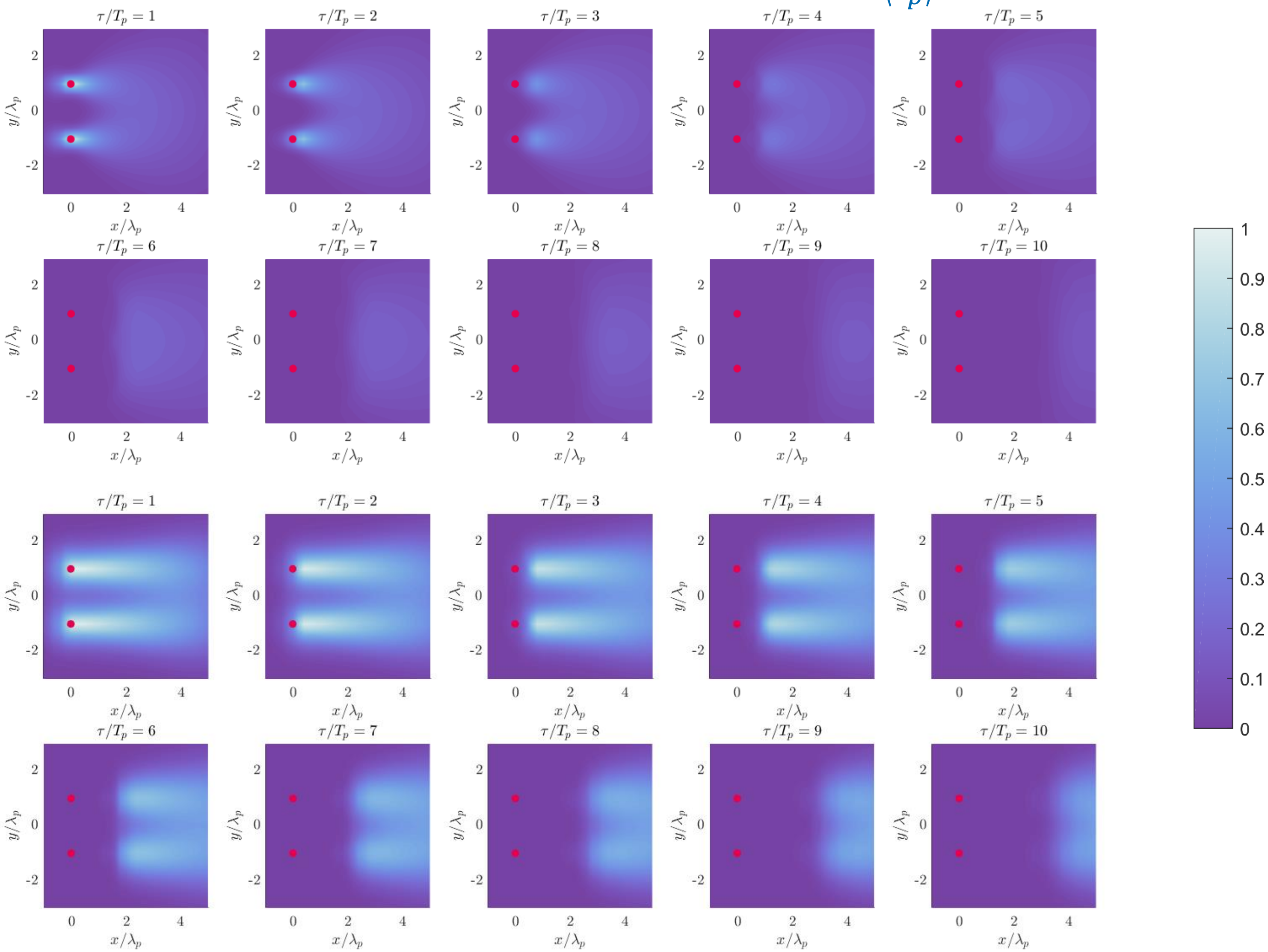
Short-crested wind sea



Long-crested swell



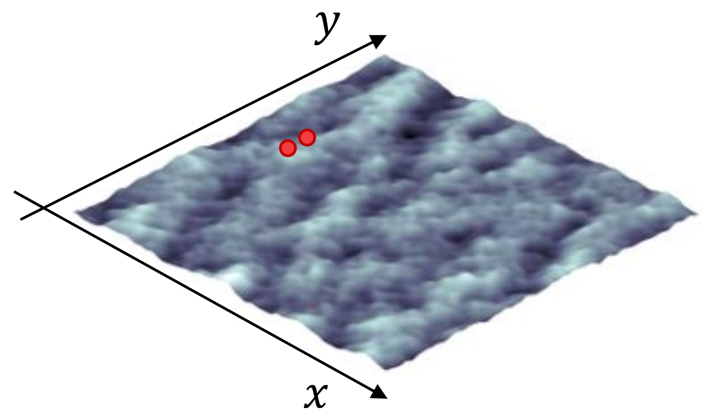
Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$



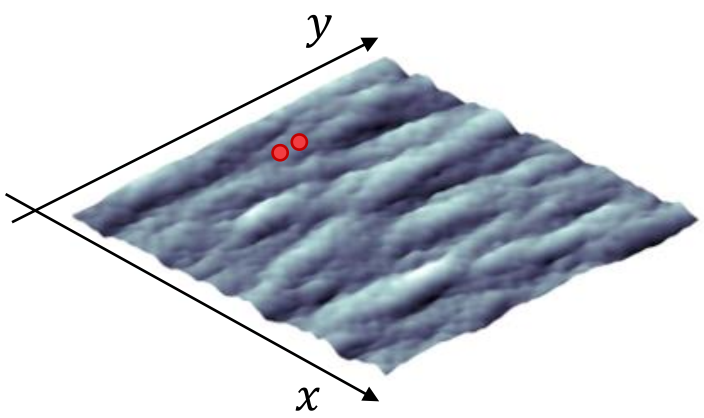
Probabilistic prediction zone in 3D

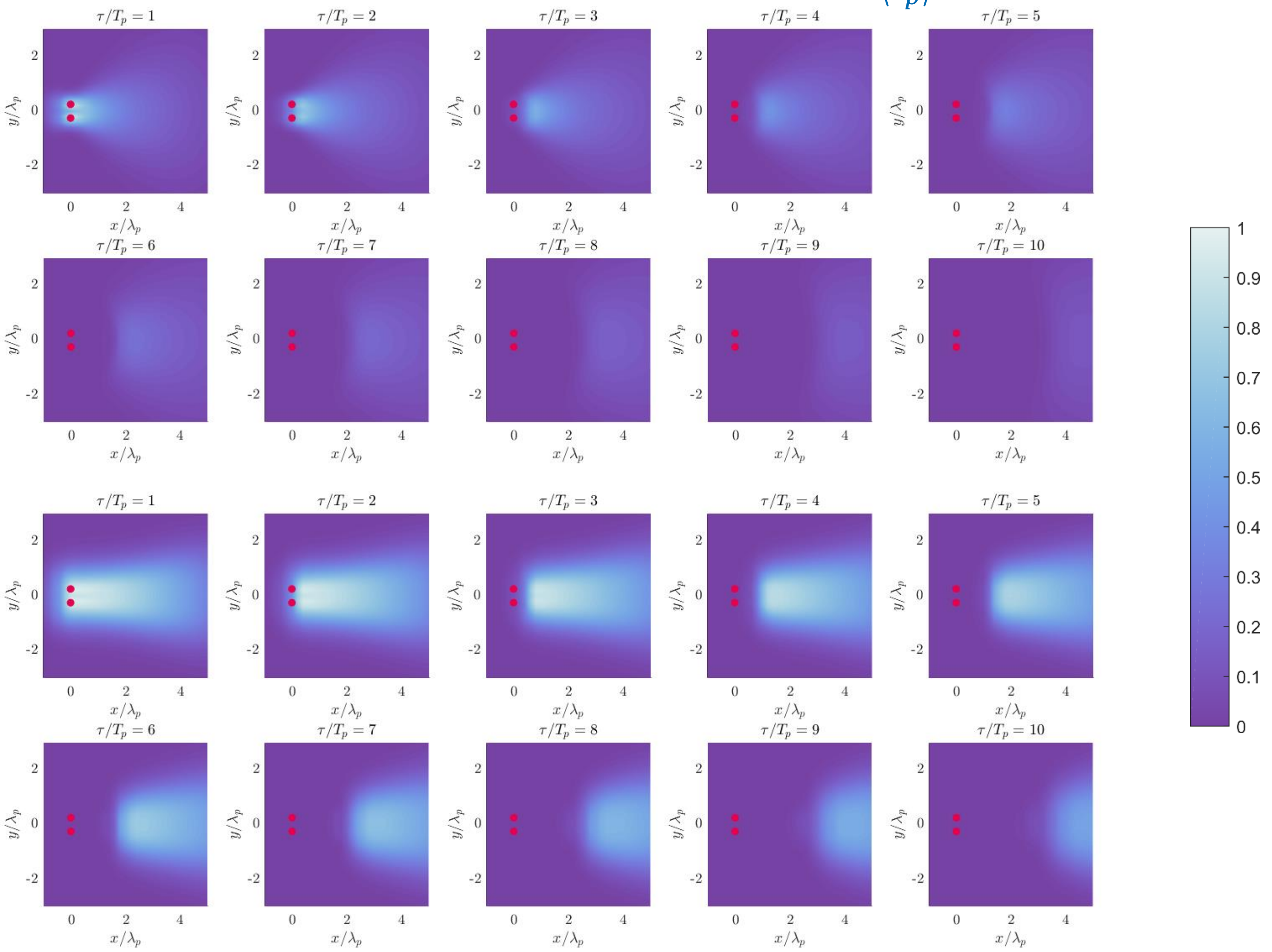
Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$

Short-crested wind sea



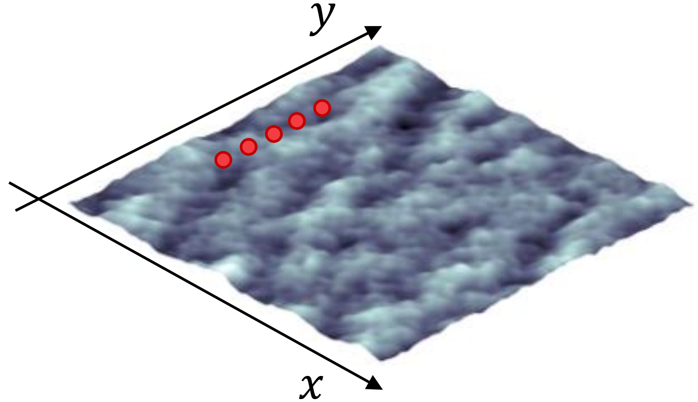
Long-crested swell



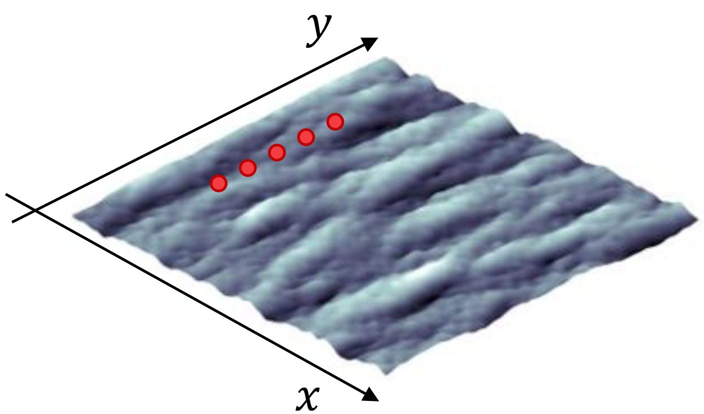


Probabilistic prediction zone in 3D

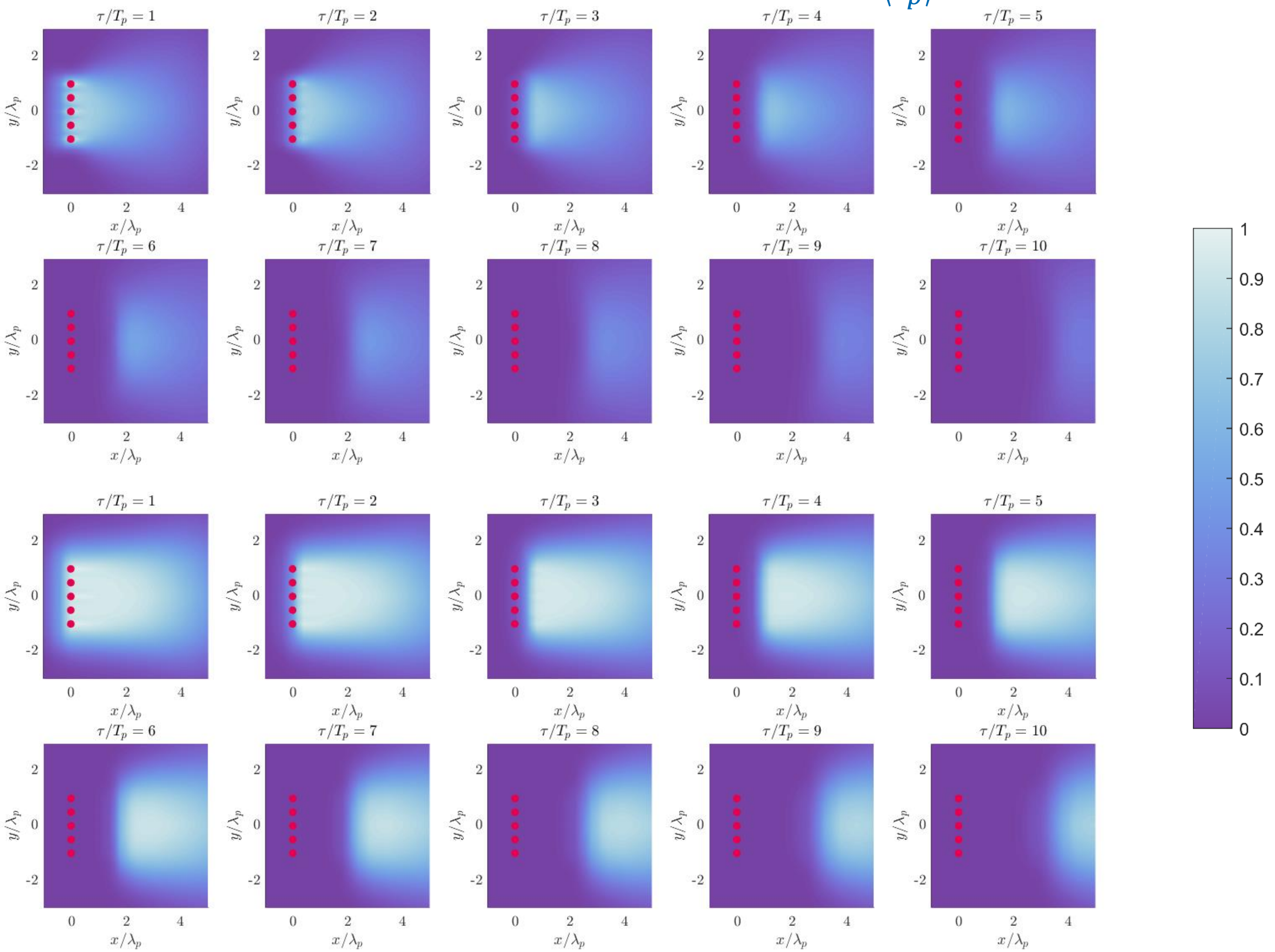
Short-crested wind sea



Long-crested swell

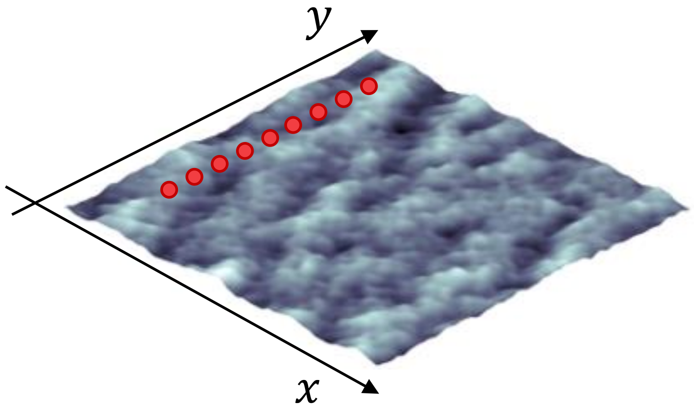


Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$

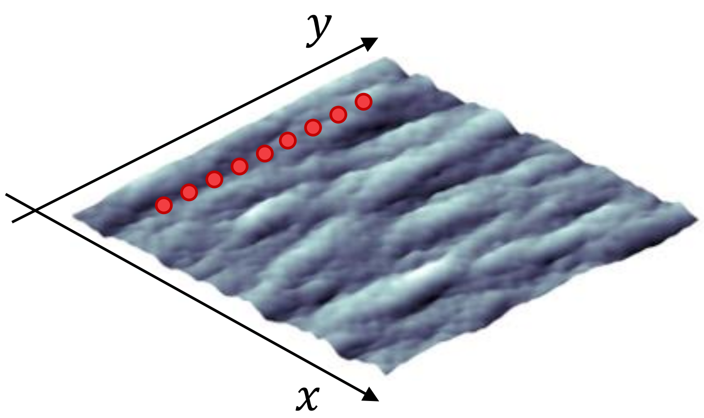


Probabilistic prediction zone in 3D

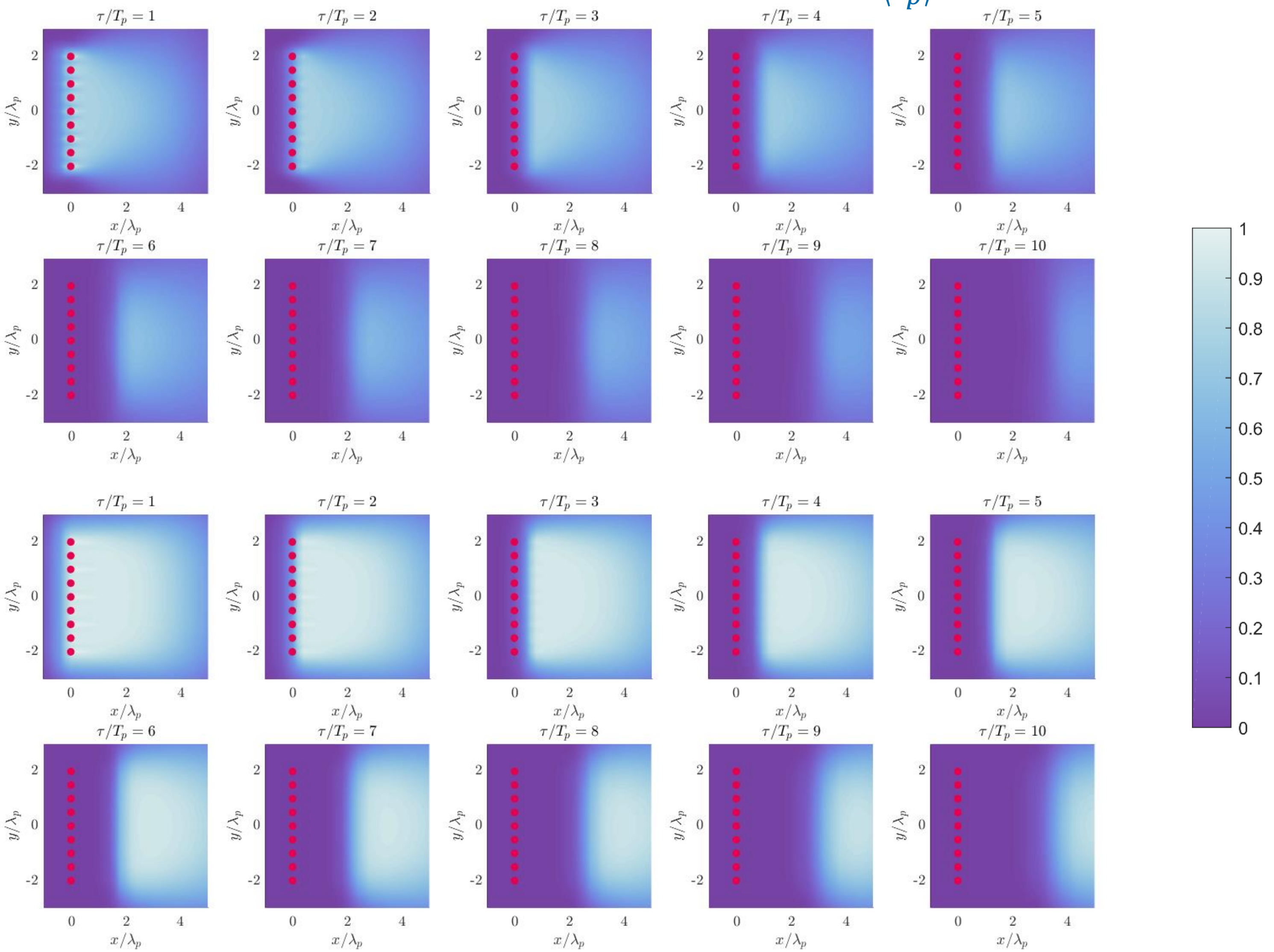
Short-crested wind sea



Long-crested swell

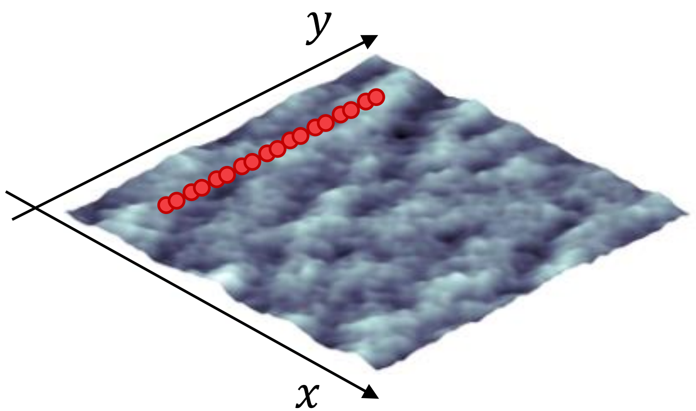


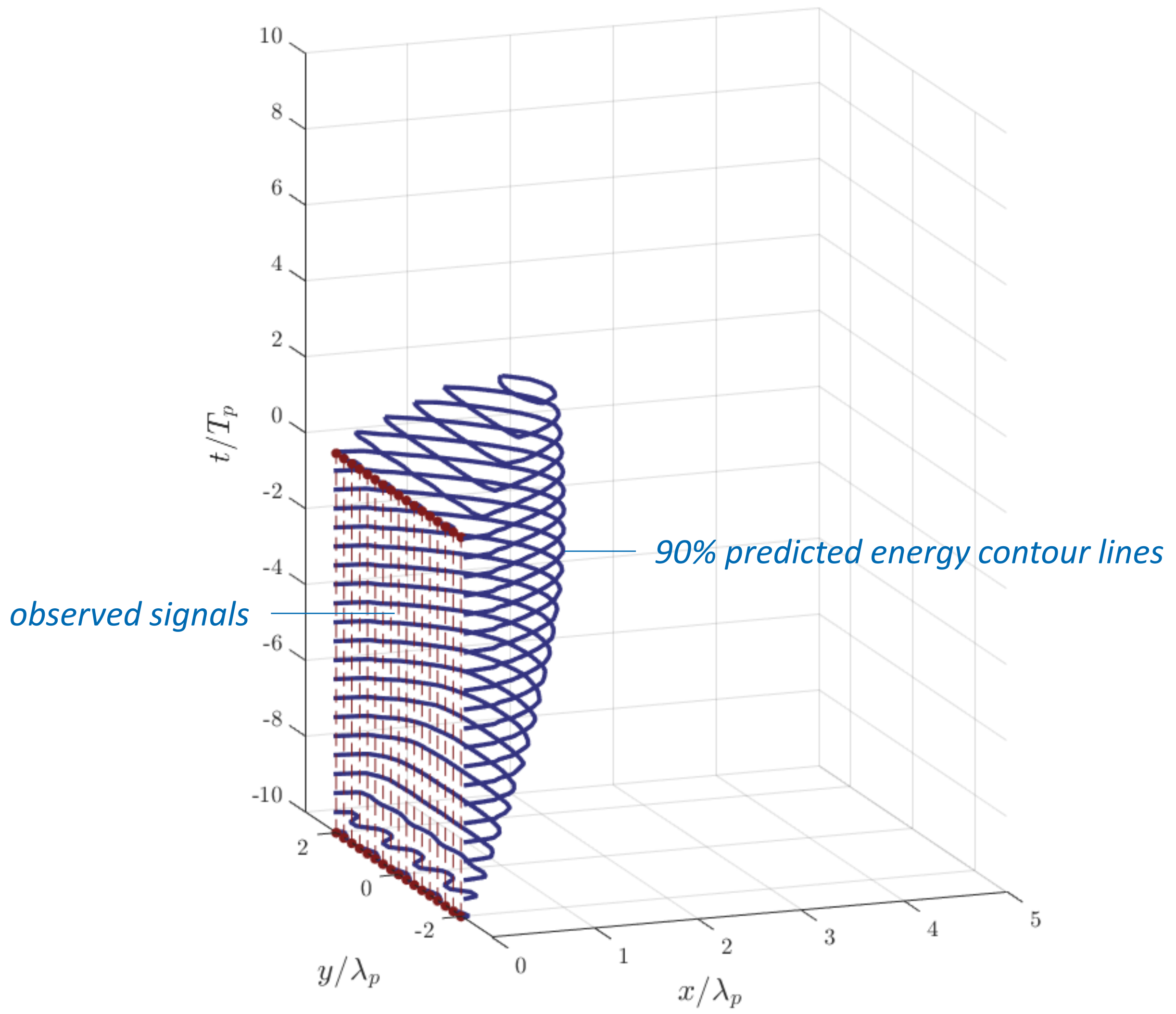
Ratio of predicted energy $r = 1 - \frac{\langle \epsilon^2 \rangle}{\langle s_p^2 \rangle}$



Probabilistic prediction zone in 3D

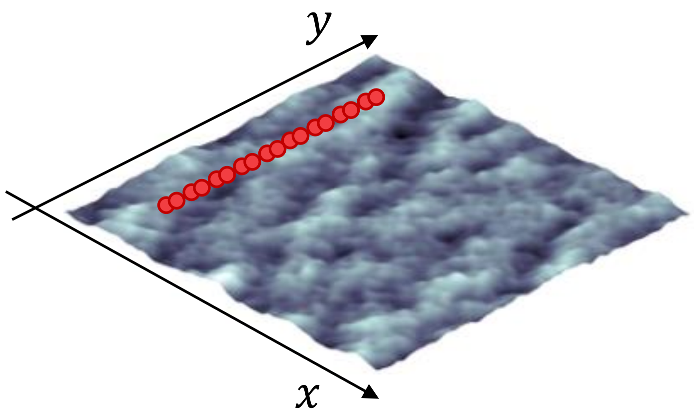
Short-crested wind sea

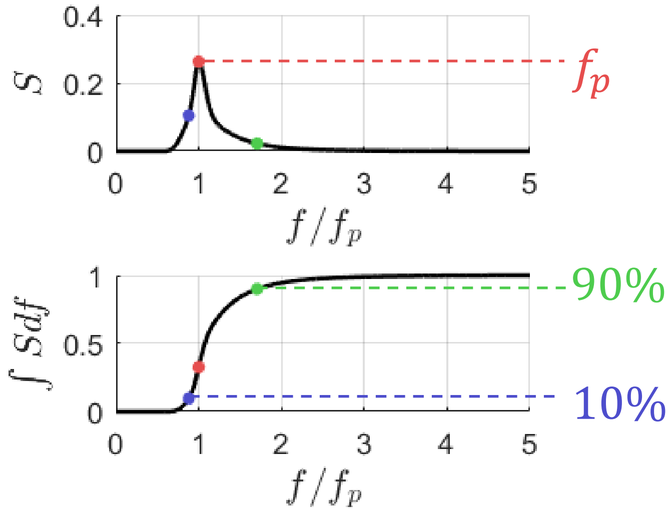


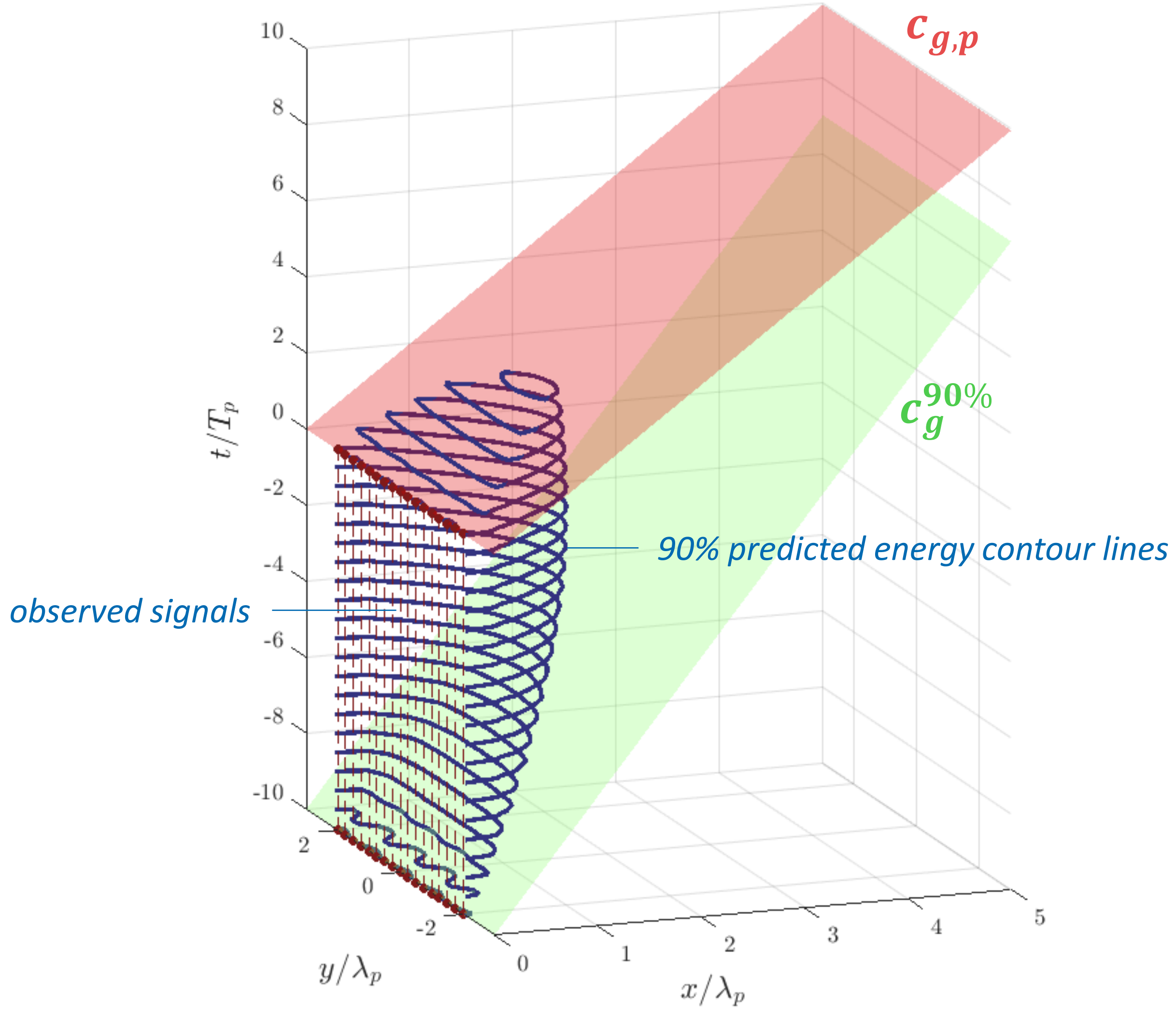


Probabilistic prediction zone in 3D

Short-crested wind sea

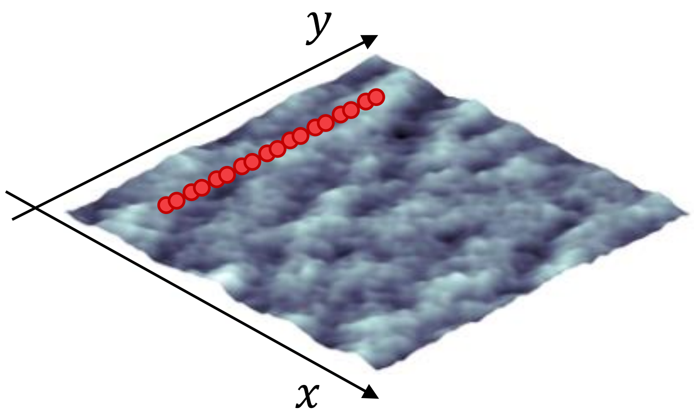




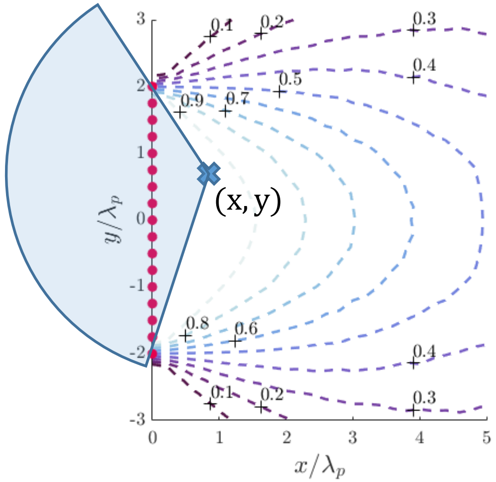


Probabilistic prediction zone in 3D

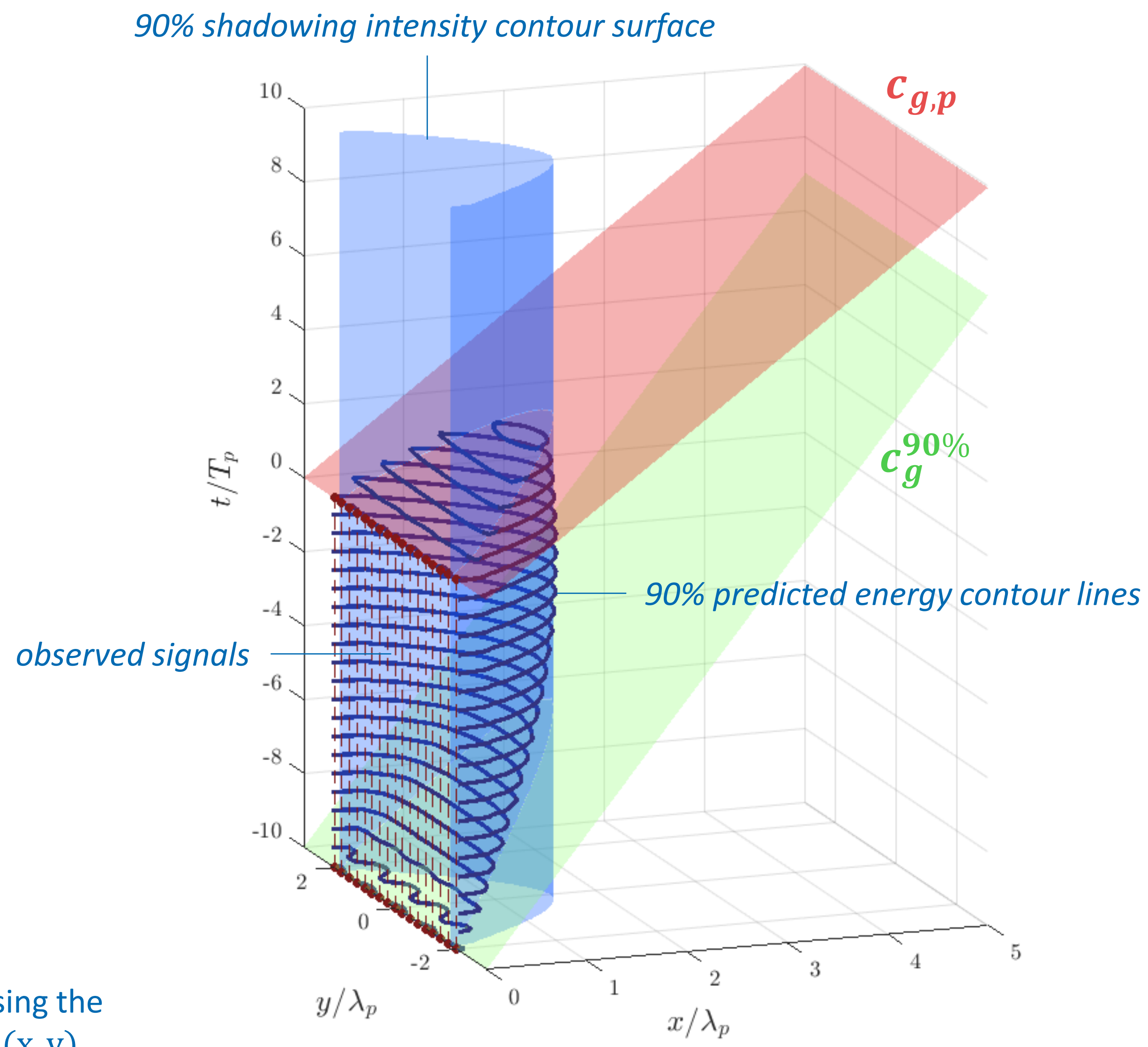
Short-crested wind sea



Shadowing intensity

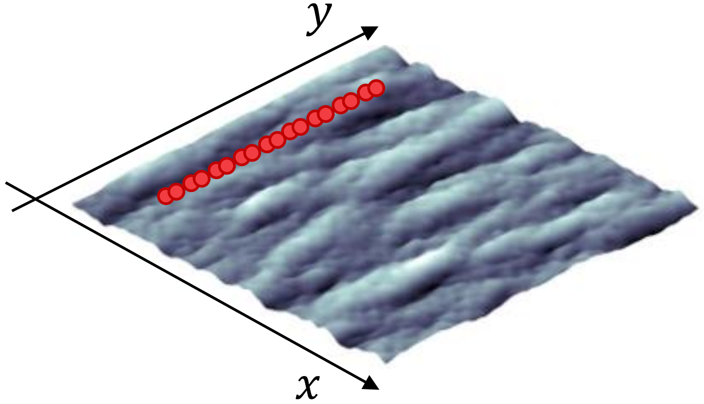


fraction of directional wave energy crossing the observation array before reaching point (x, y)

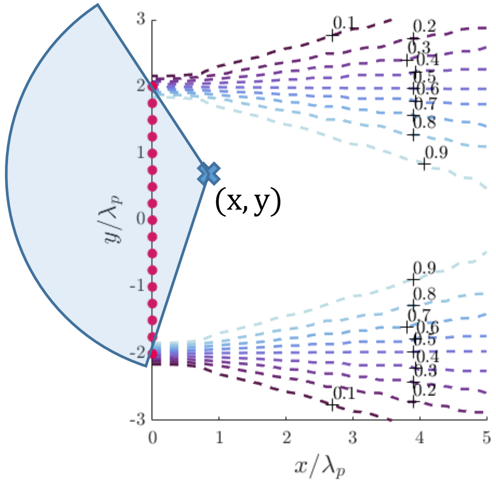


Probabilistic prediction zone in 3D

Long-crested swell



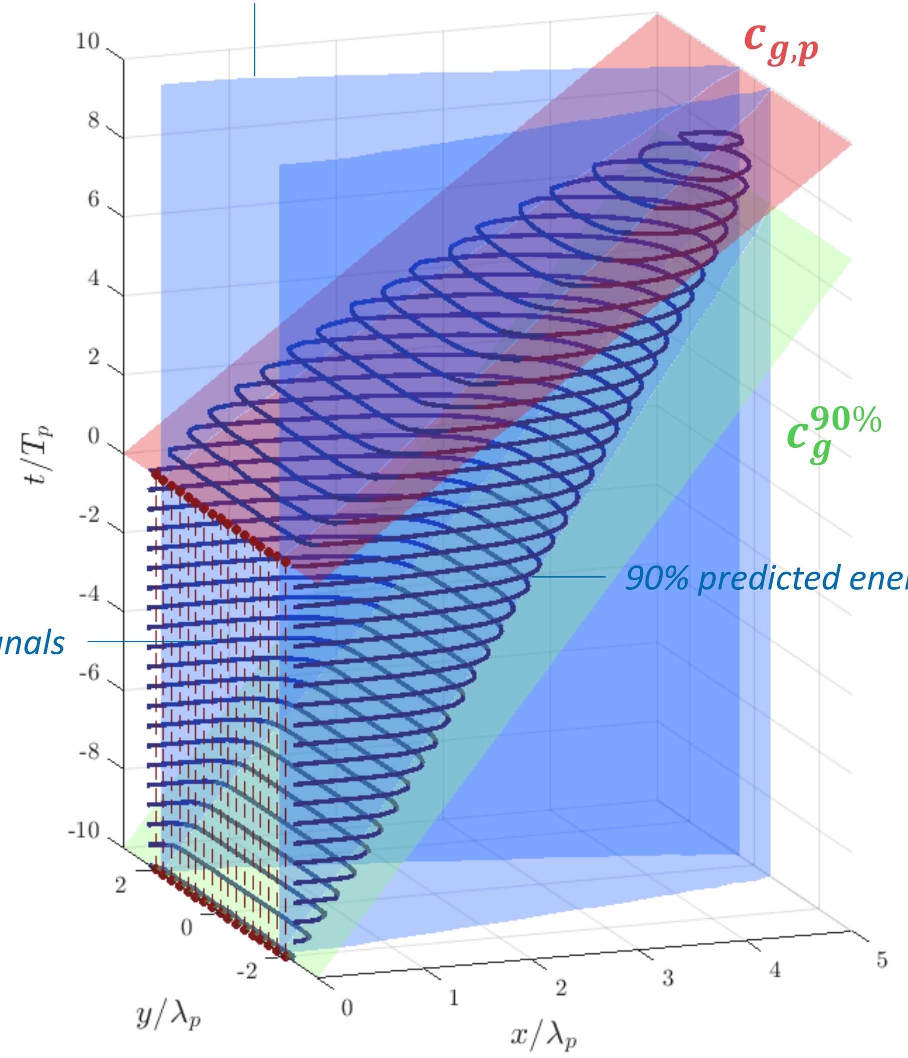
Shadowing intensity



fraction of directional wave energy crossing the observation array before reaching point (x, y)

90% shadowing intensity contour surface

observed signals



Conclusions

- There is no « deterministic prediction zone », strictly speaking.
- In 2D, the shape of probabilistic prediction zones, defined by desired error thresholds, can be geometrically approximated from two group velocities:
  - An energy cutoff threshold for the minimum group velocity
  - The peak frequency for the maximum group velocity
- In 2D, the forecasting horizon can be extended indefinitely.
- In 3D, arrays of closely-spaced ($\approx \frac{\lambda_p}{2}$) observation points are required to obtain appreciable prediction zones.
- In 3D, the min and max group velocities of the 2D case provide upper and lower bounds to the prediction zones.
- In 3D, the « shadow intensity », cast by the array, provides an envelope that further limits the extent of the prediction zones.

alexis.merigaud@ifpen.fr

paolino.tona@ifpen.fr

Innovating for energy

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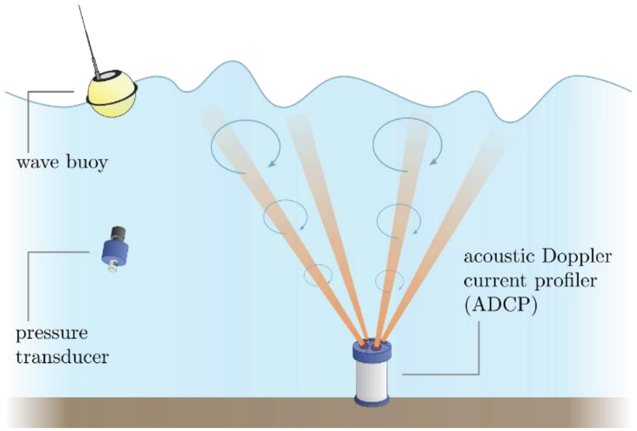
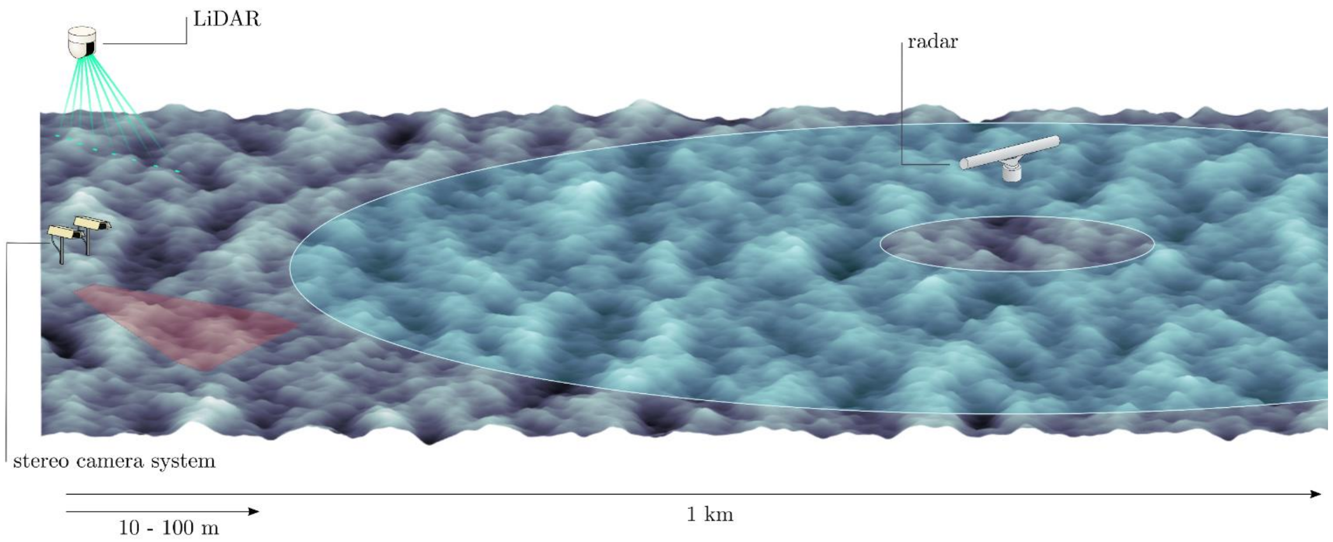
Wave-by-wave forecasting paradigms

Point measurements



Distributed measurements



Other observation layouts