The DeRisk design database: extreme waves for Offshore Wind Turbines

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About me

Glaciar Perito Moreno (Argentina 2019)

- Mechanical Engineer Uni. Ancona (IT, 2007)
- PhD in wind turbine aerodynamics from NTNU (NO, 2014)
- Working with waves ever since
  - IFE (NO, 2014 – 2017)
  - DTU (DK, 2018 –)

Extreme loads from large waves: a possible design driver

- Turbines and monopiles size increases
- Waves and loads are ”Extreme” in probabilistic terms
- Stochasticity needs to be handled together with nonlinearity of the waves

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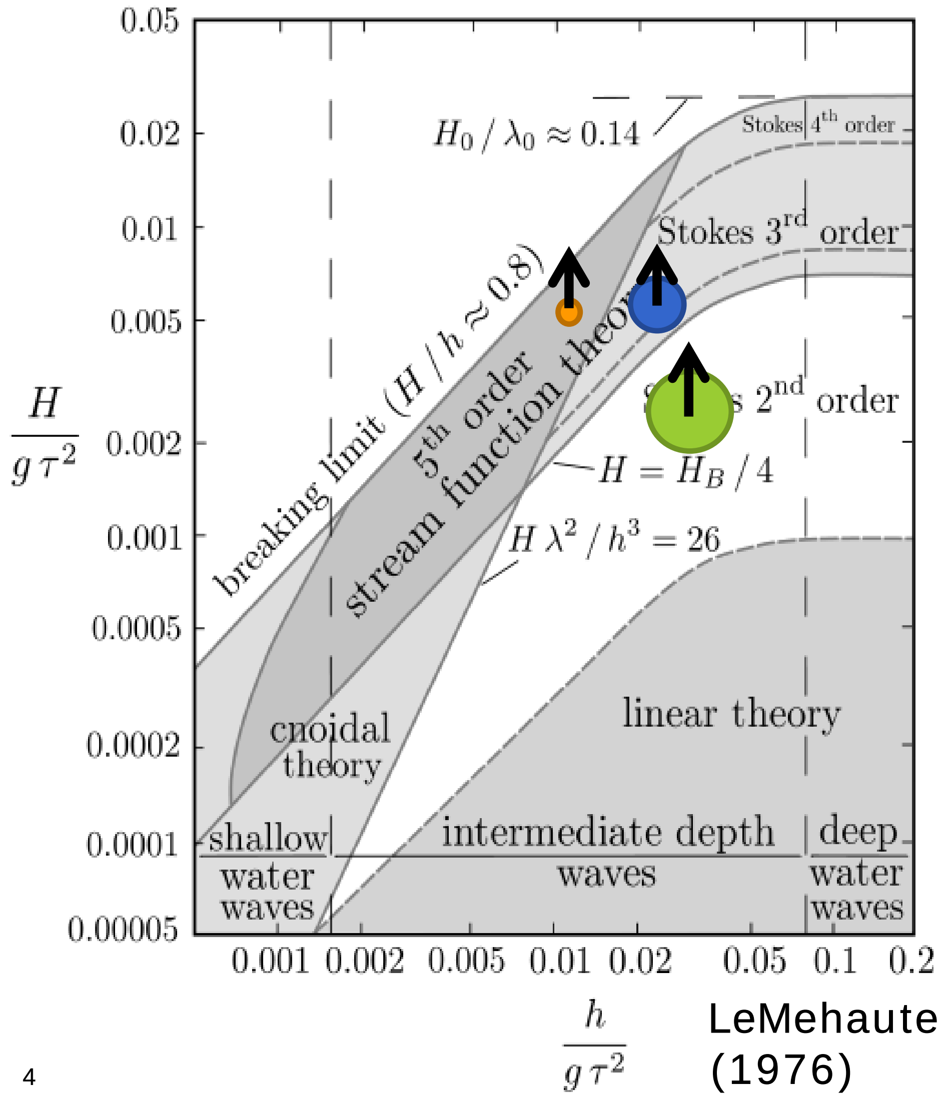
Sea states: what does an Offshore Wind Turbine (OWT) experience?



LeMehaute (1976)

At $h = 22\ [m]$ depth

– Operational
– $H_S = 1[m];\ T_P = 6[s]$
– $H_S = 6[m];\ T_P = 9.5[s]$

– ULS
– $H_S = 9.5\ [m];\ T_P = 12[s]$

– 1.86 x H_S

Standard IEC61400-3 annex D: extreme waves for design

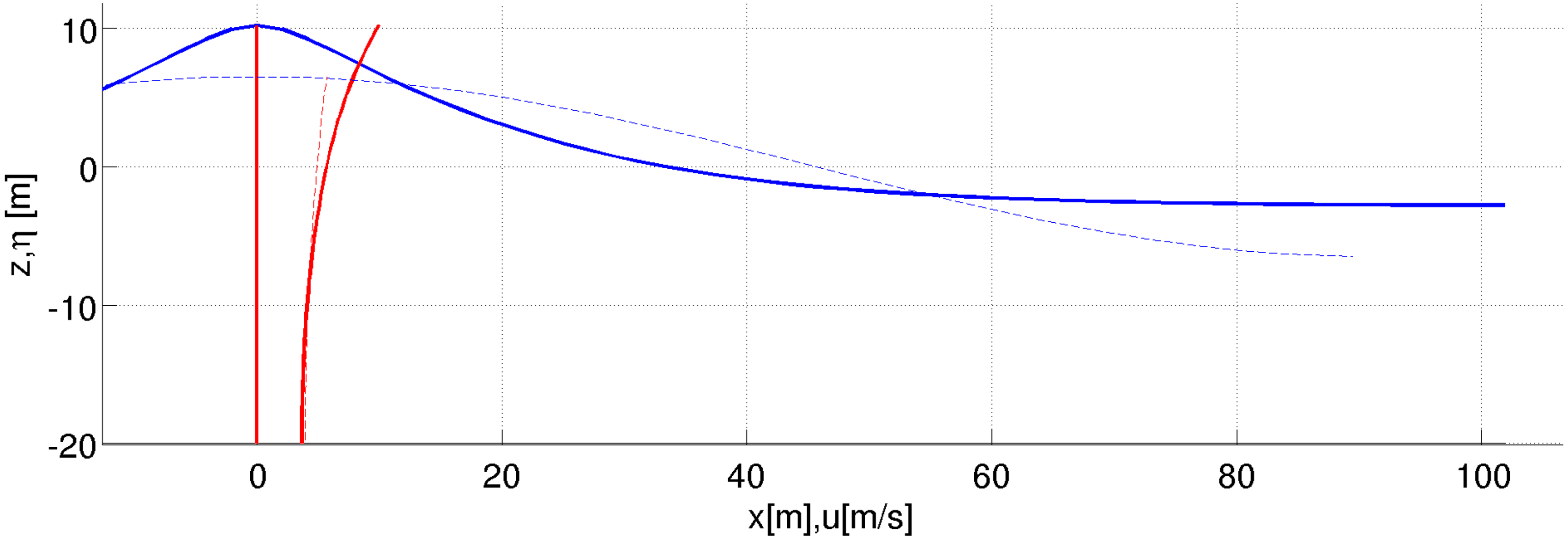
- D.7.1: Explicit approach
  - Many realizations of fully nonlinear waves

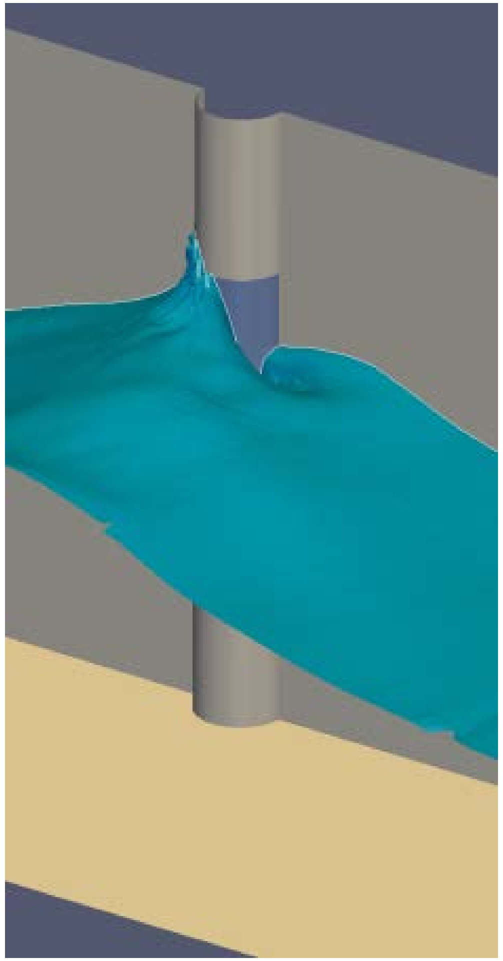
Our Approach

- D.7.2 Wave non-linearity factor approach
- D.7.3 Regular wave approach
- D.7.4 Constrained wave approach
  - Embed a regular nonlinear wave in irregular, linear waves ”Stream Function Embedment”

Common Industry Practice

Embedment of Stream Function waves: limitations



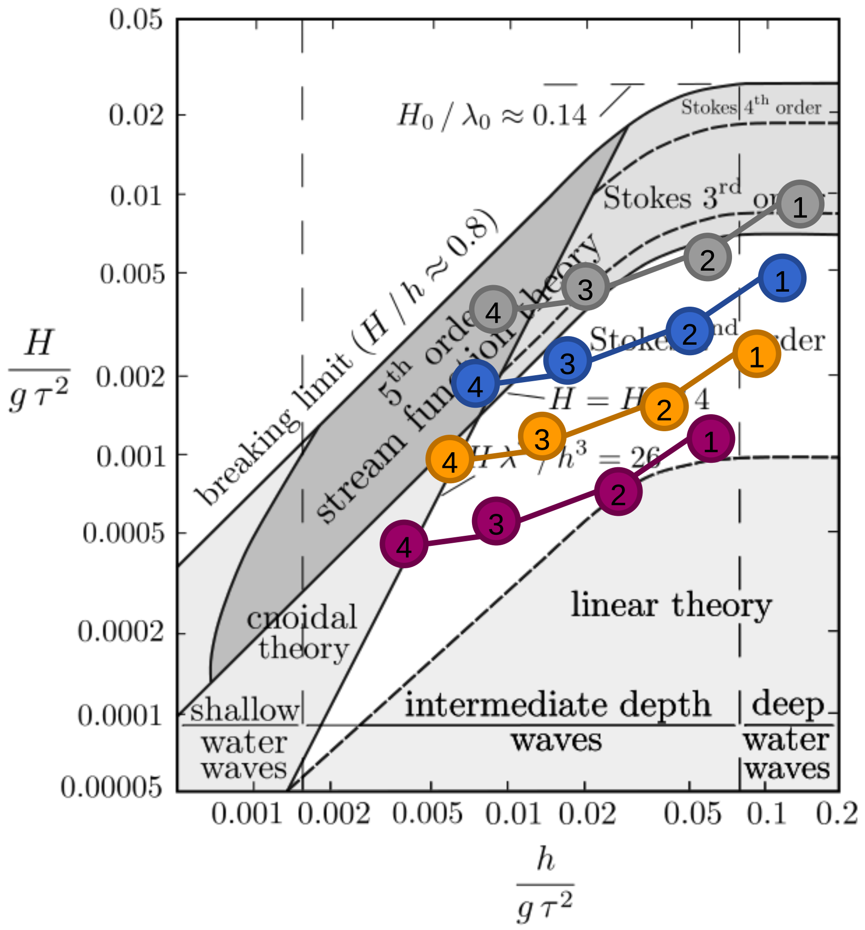


- Fully nonlinear
- Easily computed (e.g. Fenton 1988)
- Can be embedded into background state

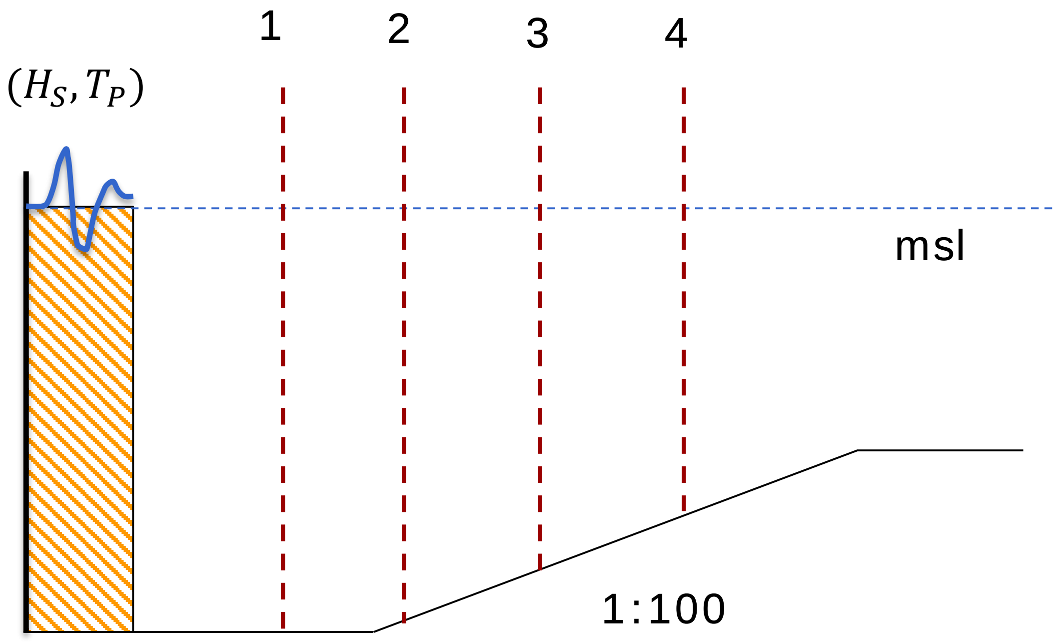
- 2D Flat bed theory
- Periodic
- Wave transformation, transient group nature, current, 3D effects?

Nonlinearity + Stochasticity: the DeRisk database

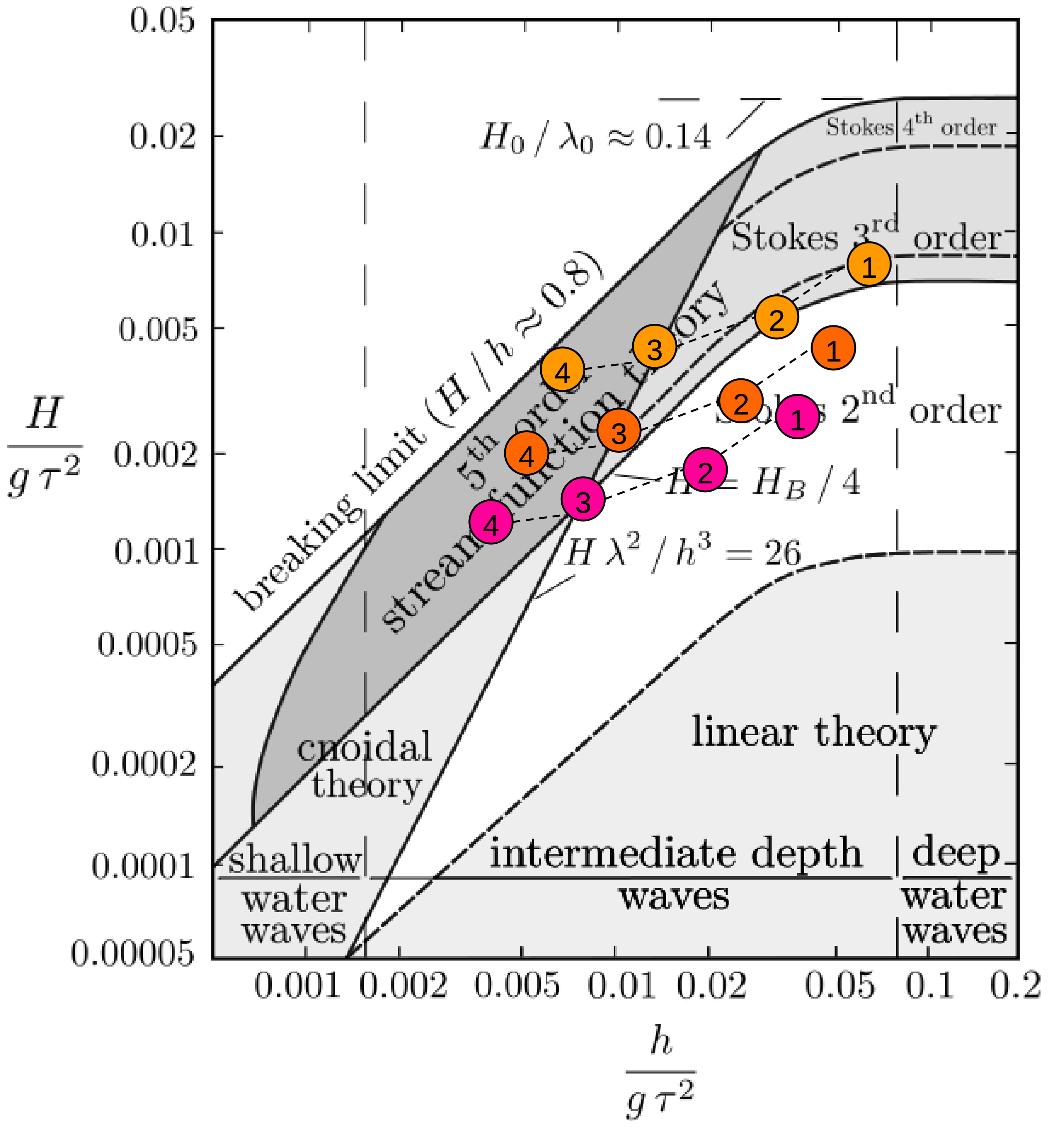
- Fundamental idea:
  - **Make a pre-computed database of fully-nonlinear extreme waves**
  - Span the nondimensional space (H,T,h)
- Make it publicly available
- Users pick suitable nonlinear kinematics
- Perform aeroelastic computations (e.g. HAWC2) by using the nonlinear input waves



The DeRisk database



SAMPLE

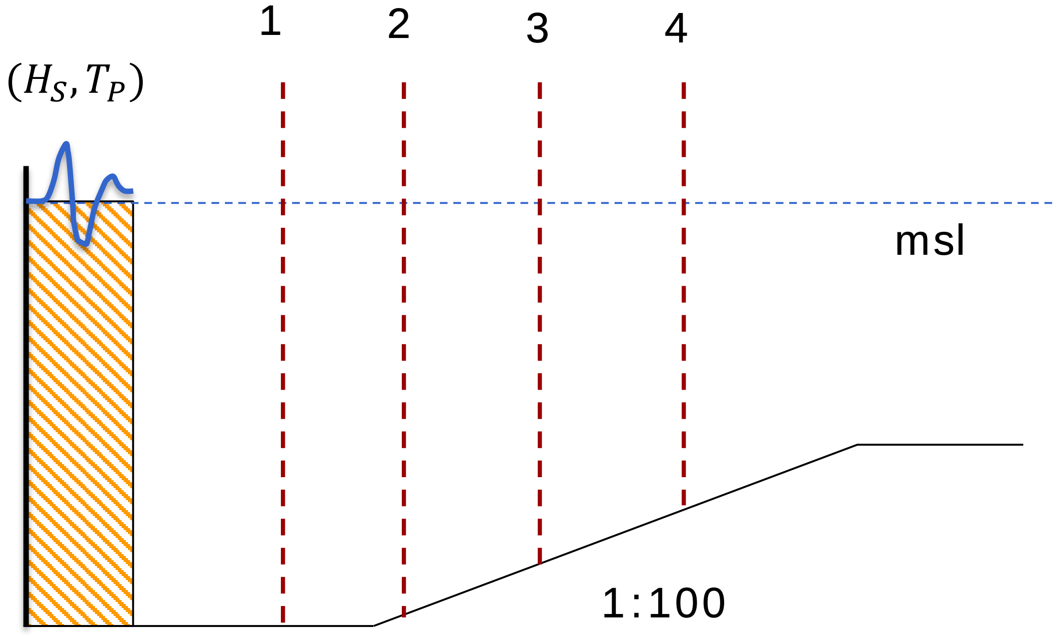


NUMERICAL MODEL

Fully-nonlinear potential wave solver OceanWave3D

(Engsig-Karup et al. 2009)

The DeRisk database



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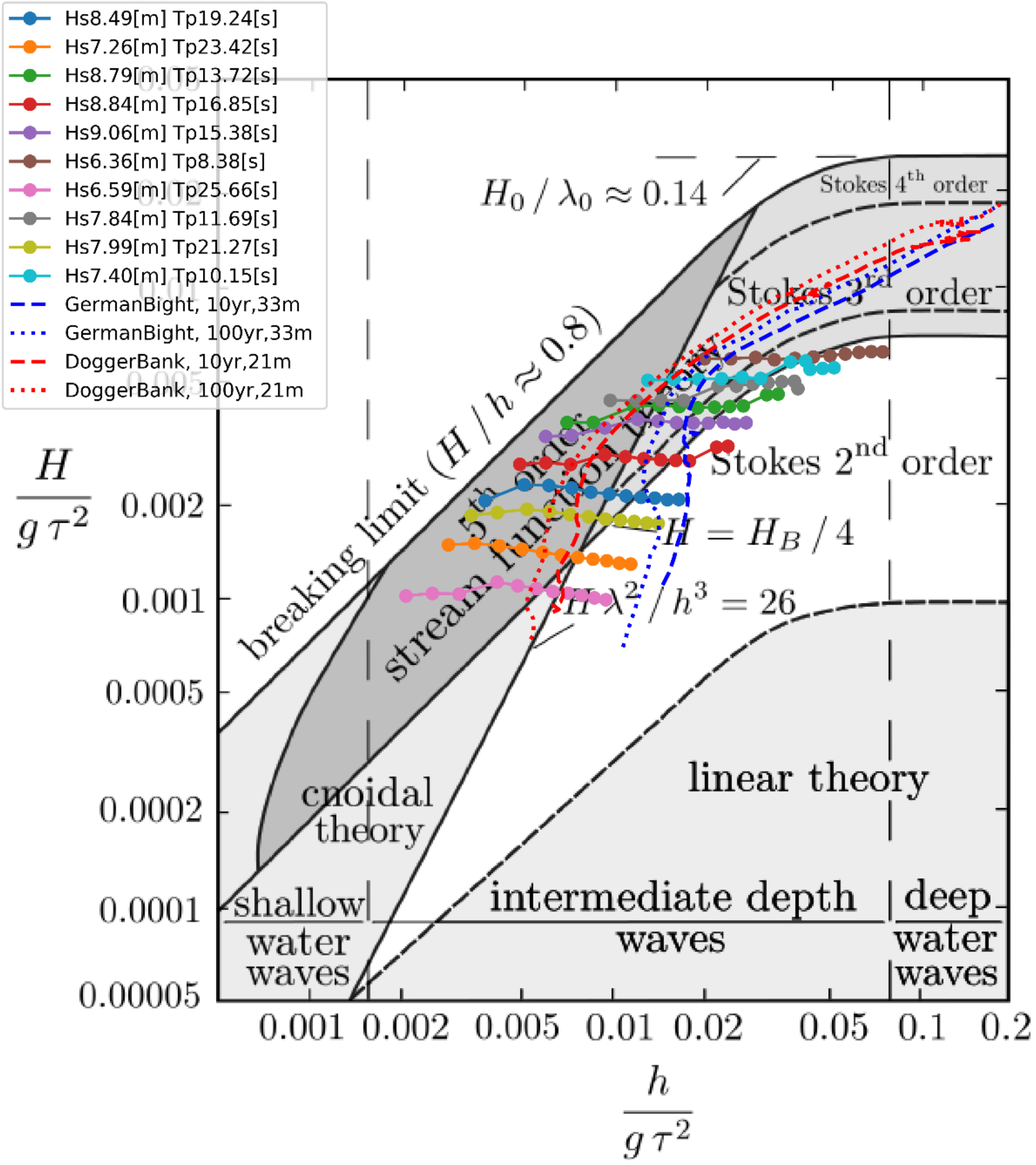

NUMERICAL MODEL

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(Engsig-Karup et al. 2009)

How to use the database: Distribution of H_S and T_P

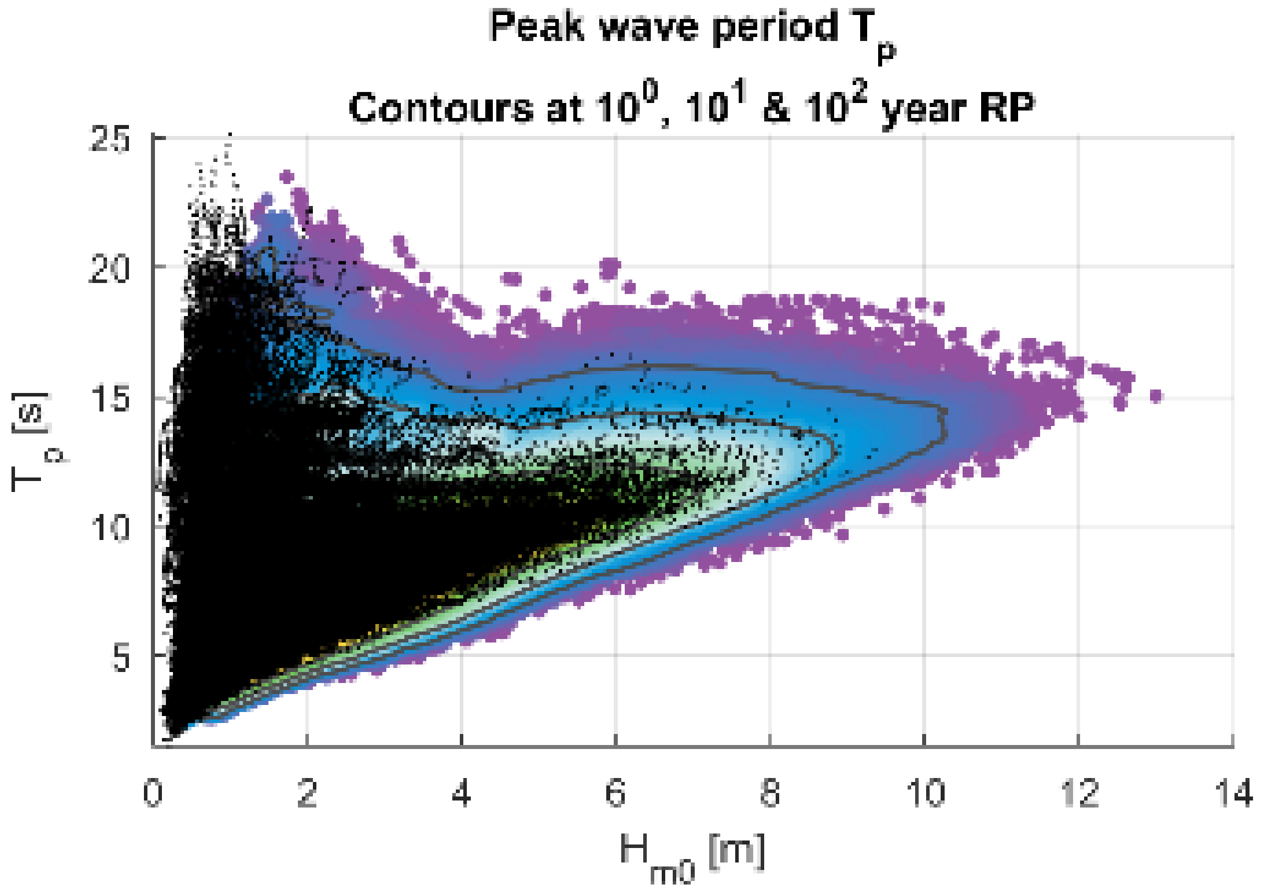
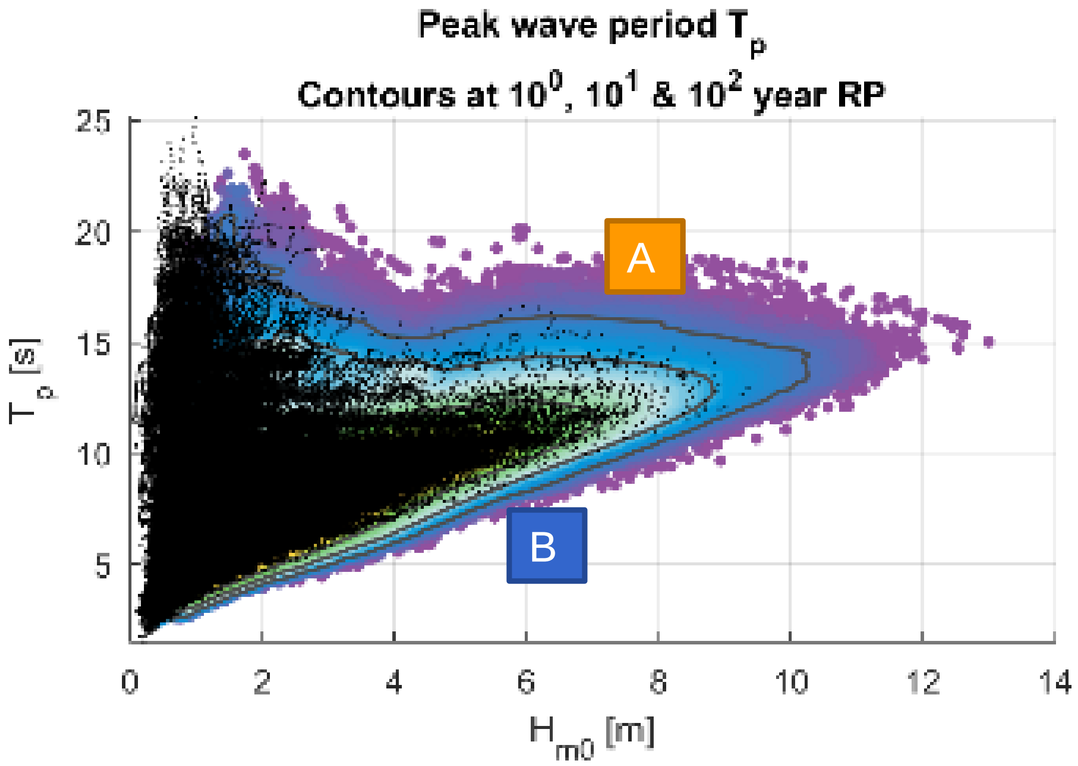


Figure courtesy of Hans F. Hansen, DHI

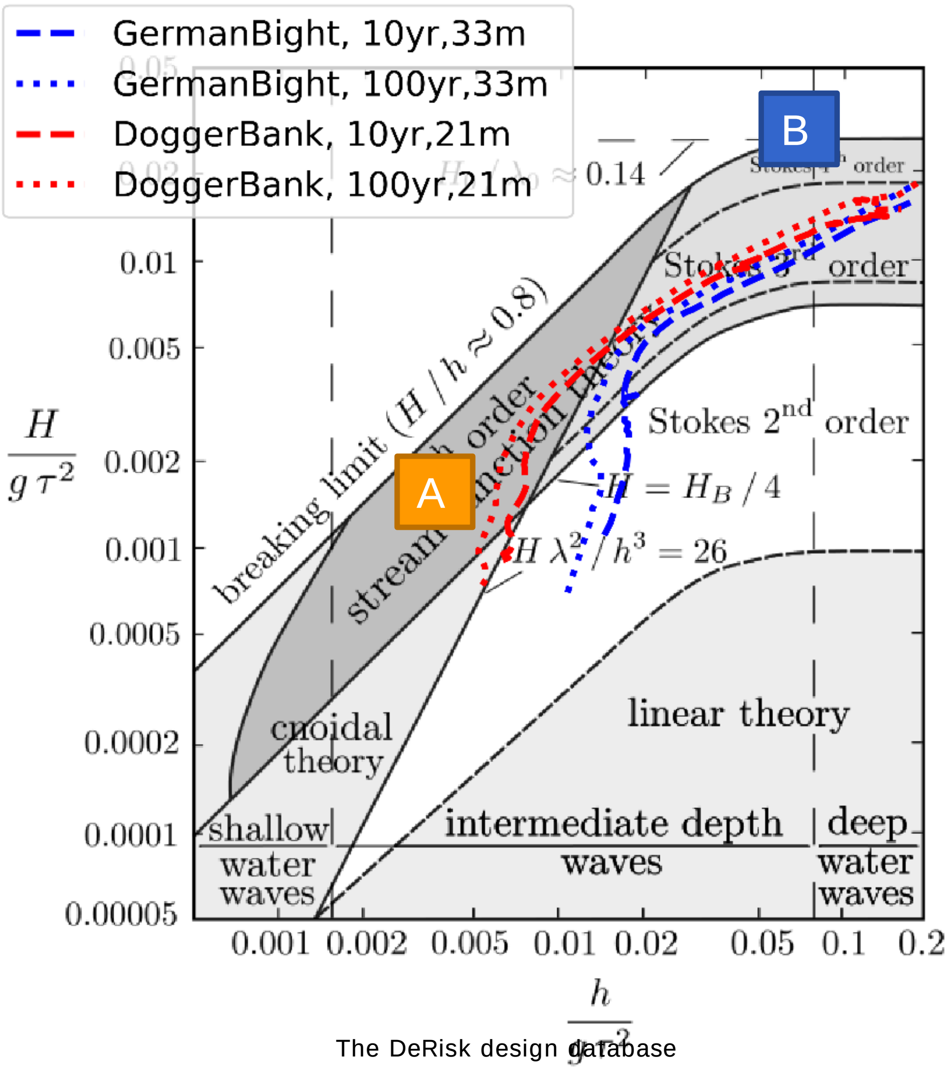
German Bight
h=33 m

How to use the database : Contour plots vs LeMehaute plot



German Bight, h=33 m

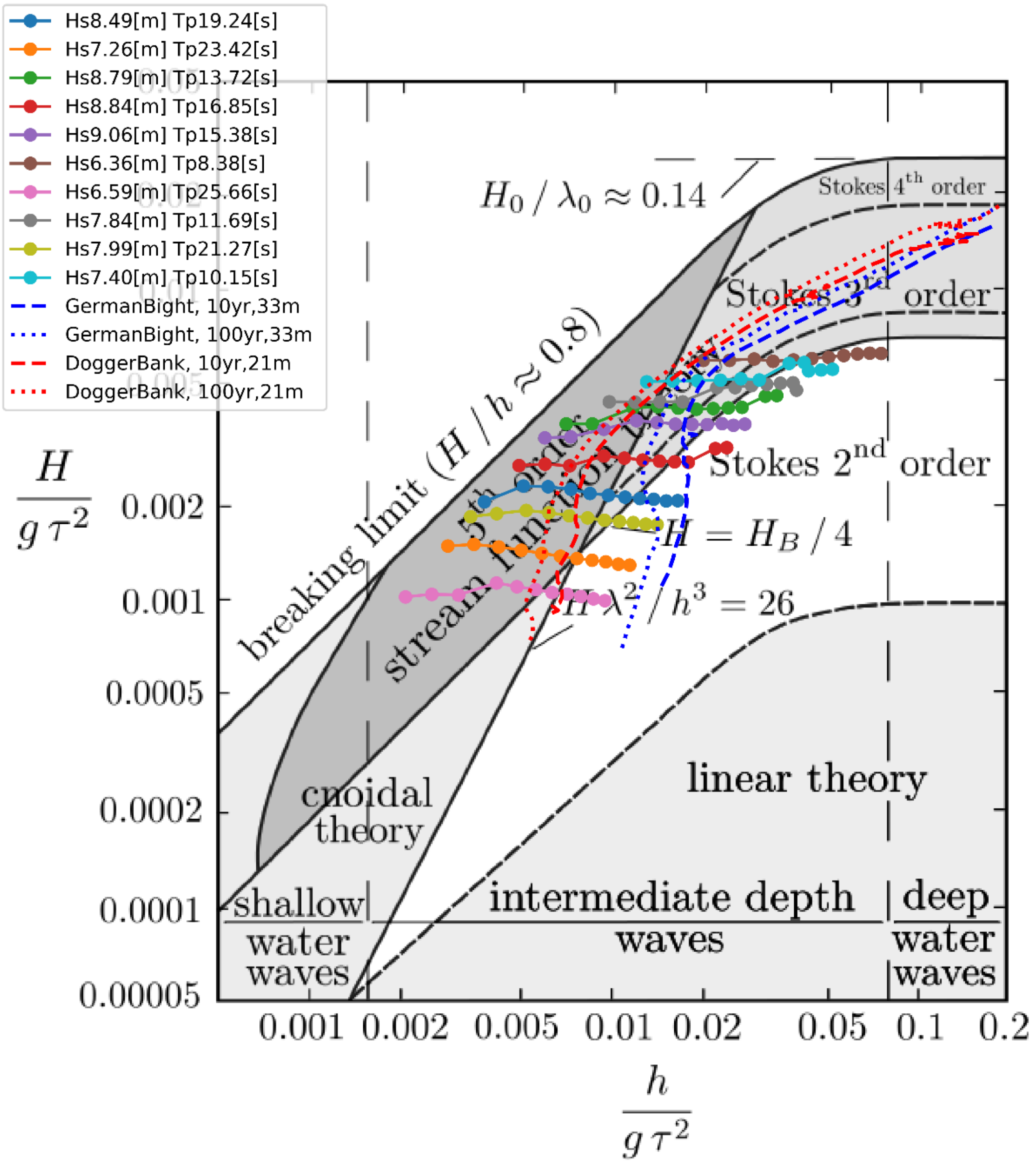
(from DHI)



How to use the database
Contour plots

- Pick a realization from the database

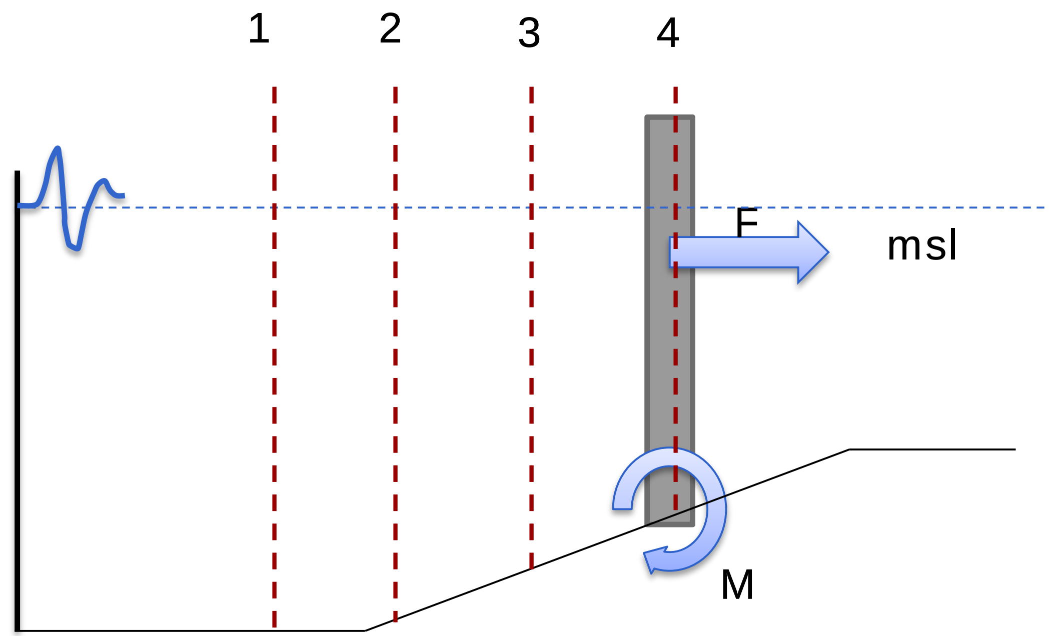
- Stochasticity
  - many 1-hr and 3-hr runs ("random seeds") for each combination of (H_S, T_P)
  - Kinematics sampled at many depths $[h = 20m \div 60m]$



How to use the database : Calculating the loads

- Use the kinematics to calculate loads on a fundation

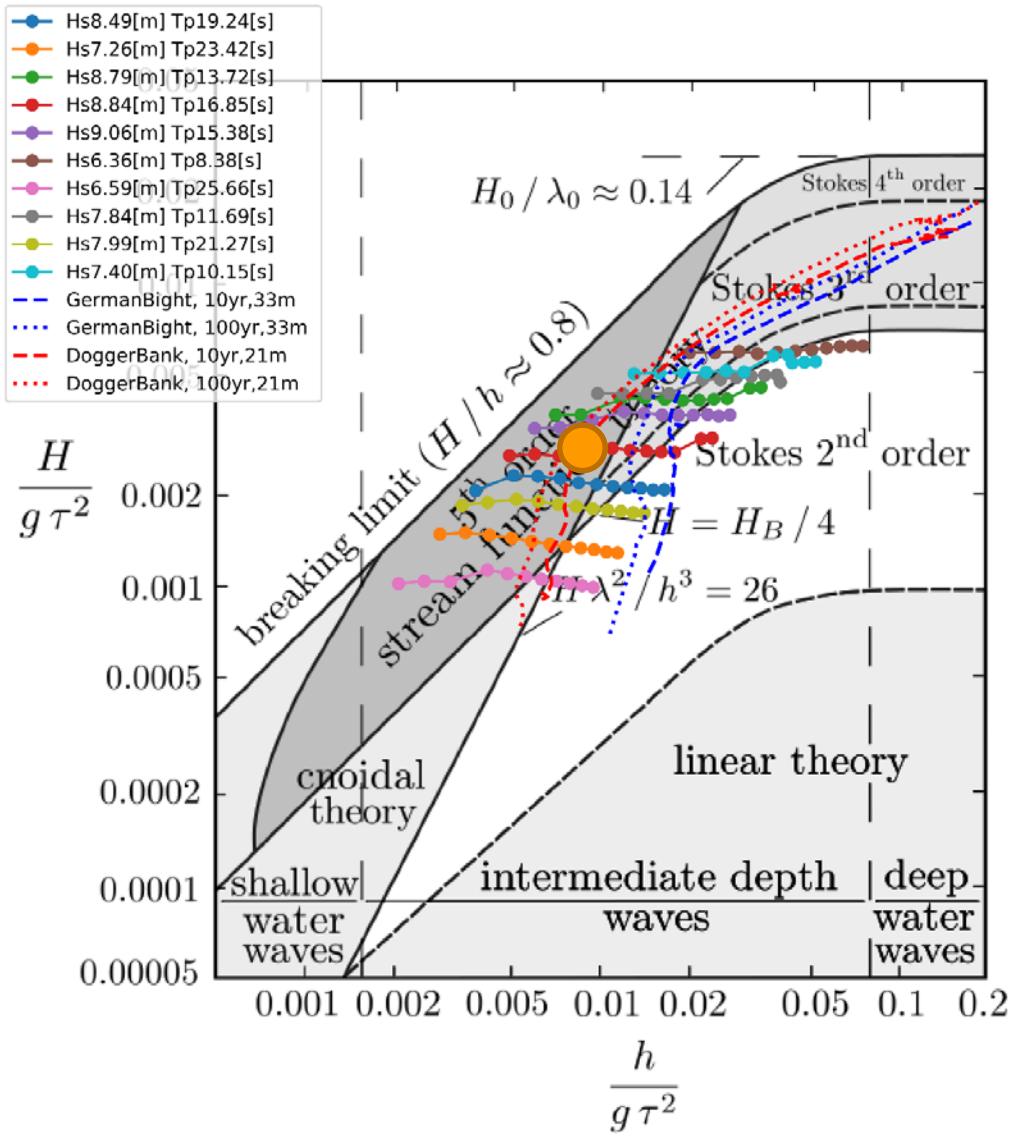
- Choose a suitable slender body force model
  - Morison (1950)
  - Rainey (1995)
  - Kristiansen and Faltinsen (2017)



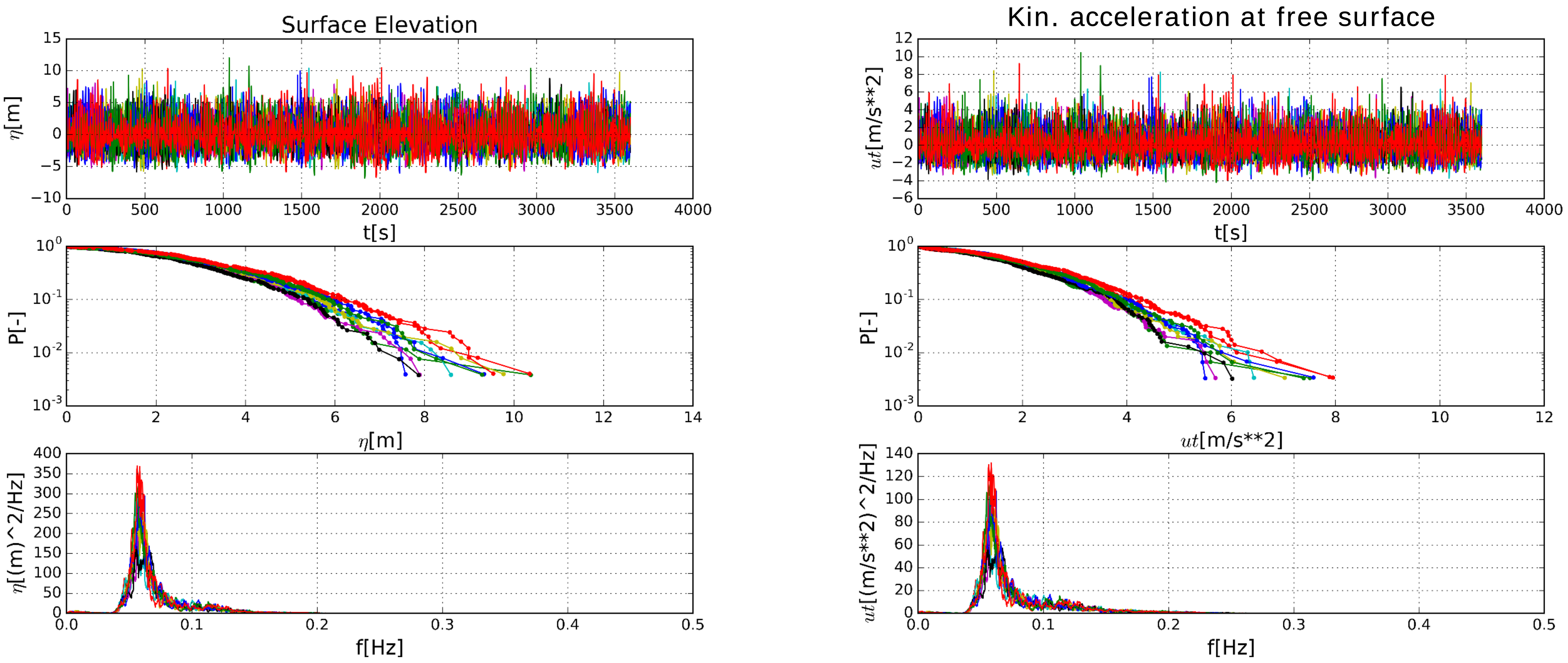
How to use the database : Load on a monopile

- We use a hypothetic monopile at German Bight
  - D = 7 [m]
  - $C_M = 2$ $C_D = 0.7$ (DNV-RP-205, 2007)
  - Stiff monopile
  - Rainey force model (Rainey 1995)

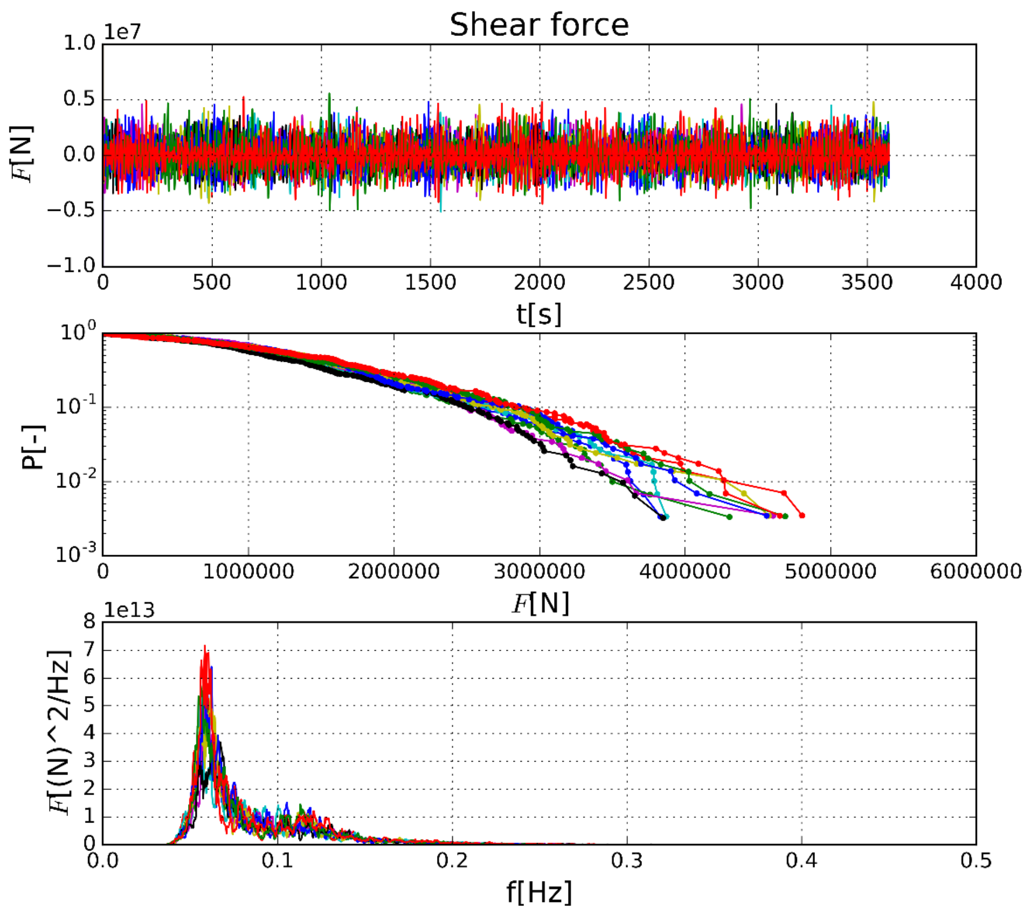
- *We got lucky!*
  We have a simulation which has kinematics sampled at h=30 [m] and which corresponds to a 100-yr storm
  - *Hs = 8.84 [m]*
  - *Tp=16.85 [s]*

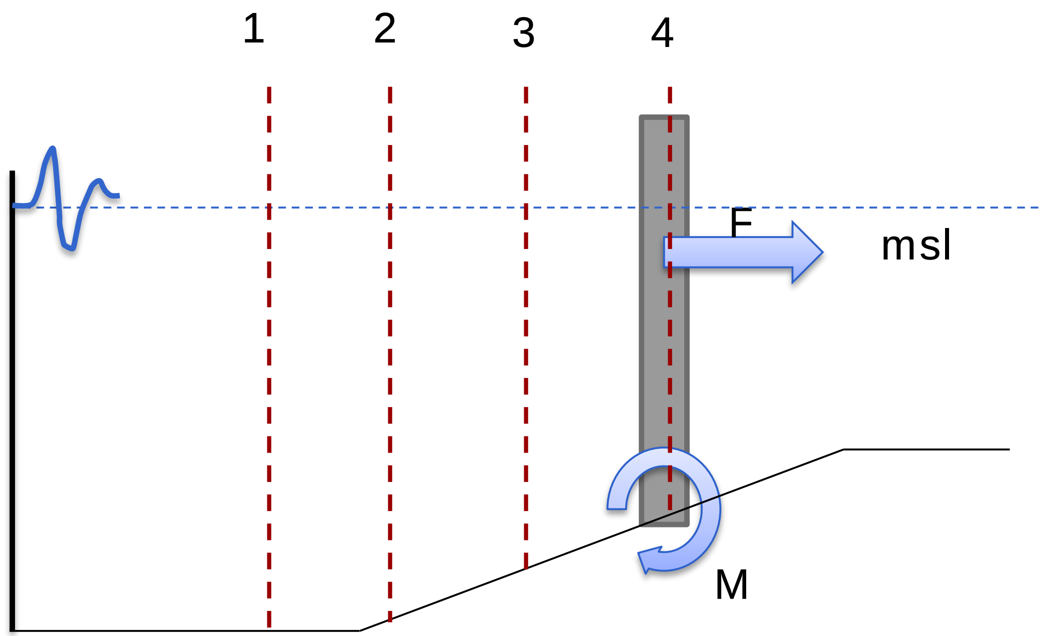


How to use the database : wave elevation and acceleration at free surface

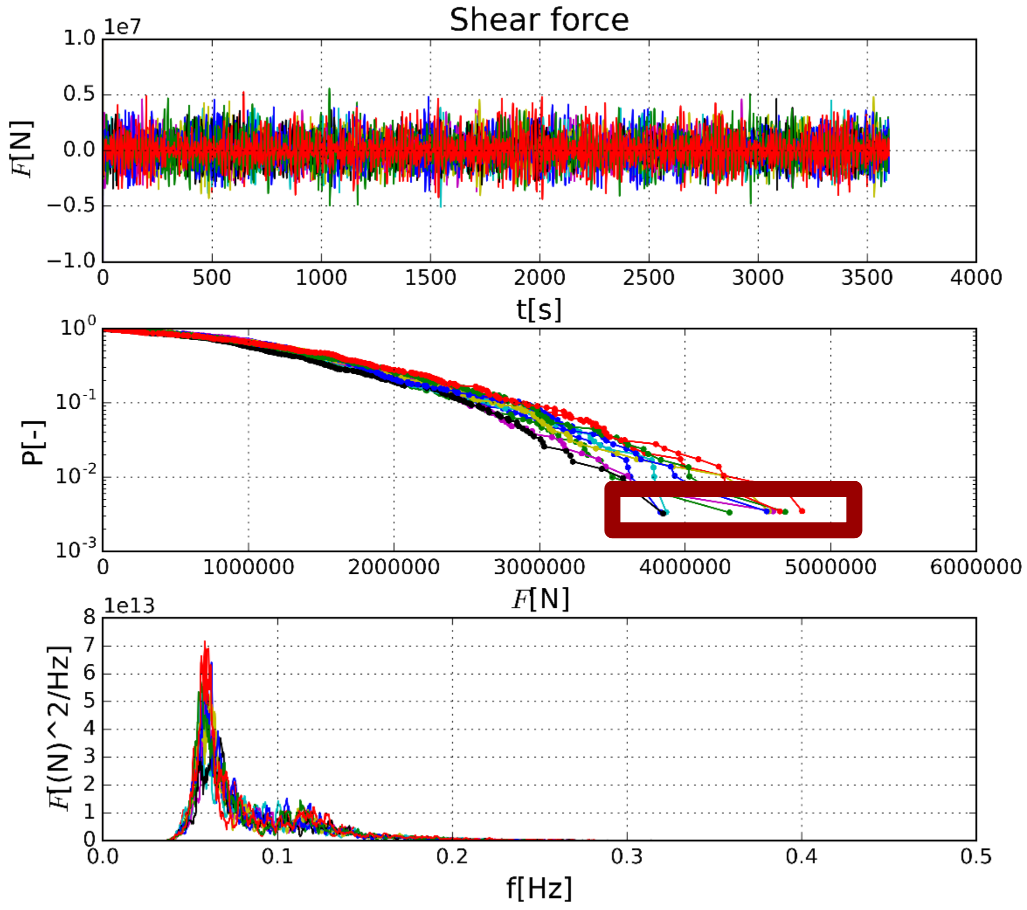


How to use the database :
Example of extreme value computation

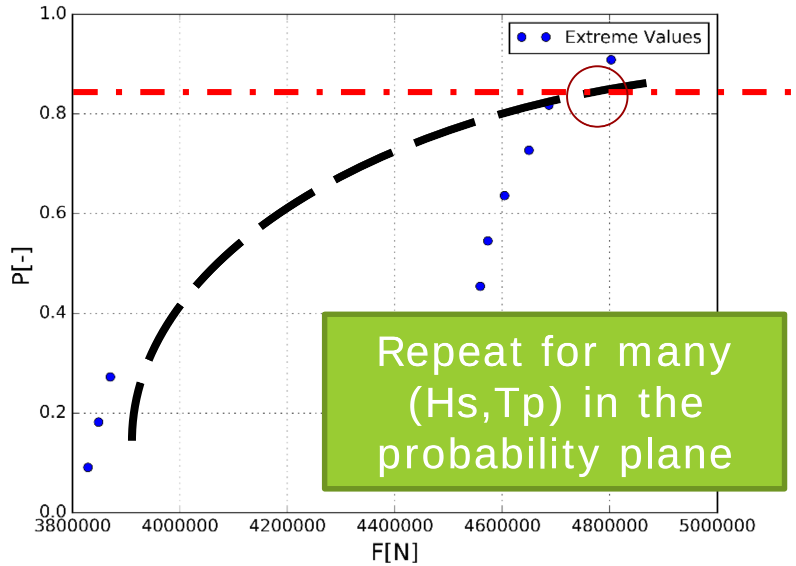




How to use the database : Example of extreme value computation



Hs = 8.84 [m]; Tp=16.85 [s]



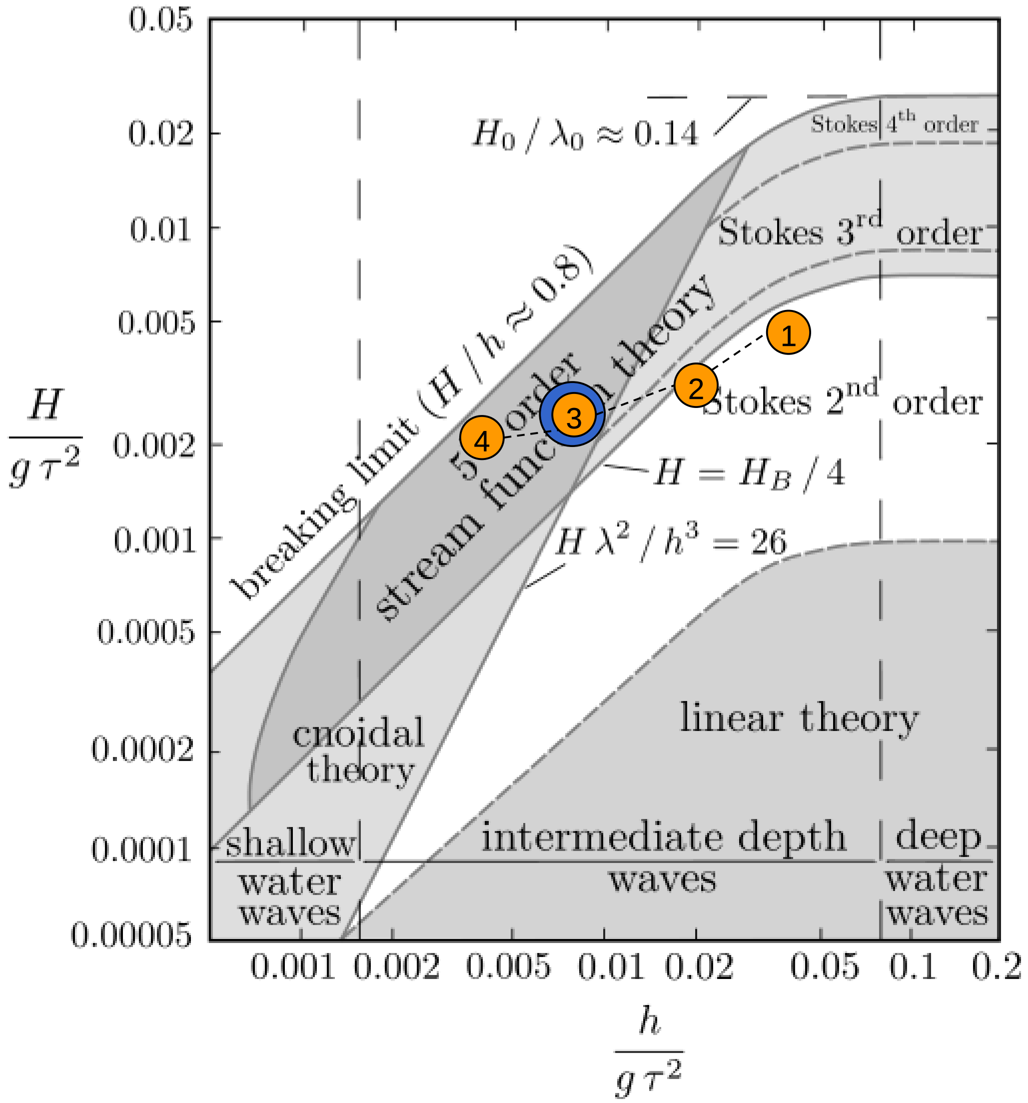
Fit an extreme distribution (Gumbel, GEV...) to the non-exceedance probability and estimate confidence level for extreme value

How to extend the database : Froude scaling

- Waves are kinematically similar if they have the same Froude Number

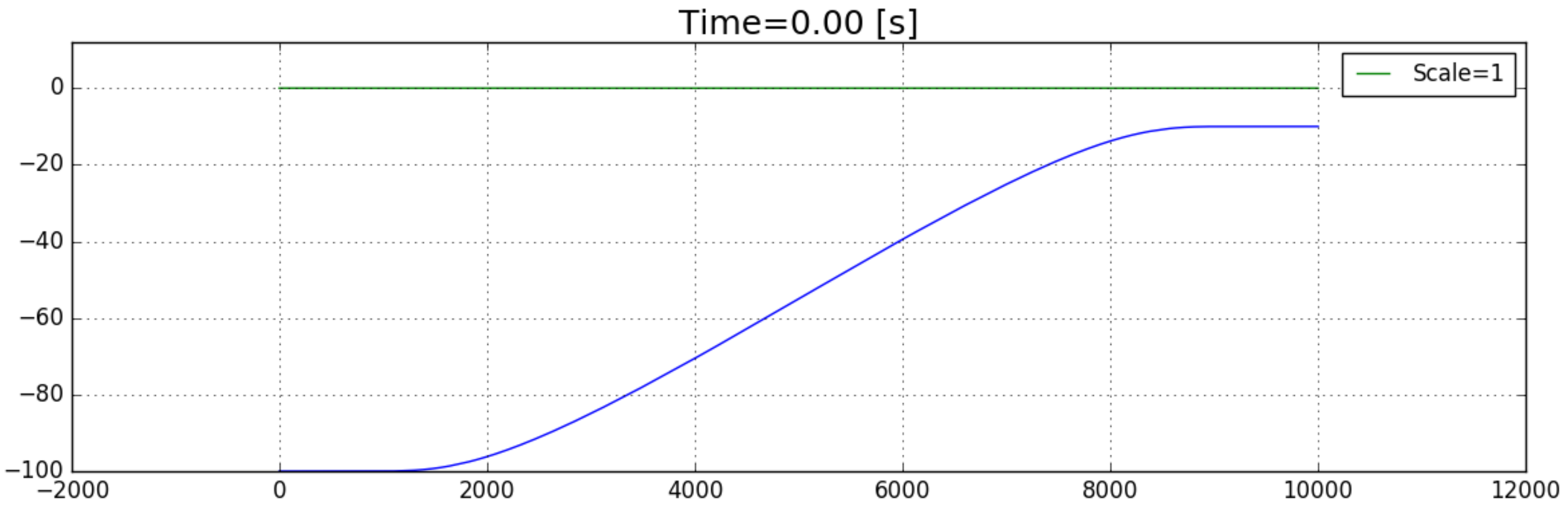
$$Fr = \frac{L}{gT^2}$$

  - "Real life" wind farm
    - $(H_S, T_P, h) = (6[\text{m}], 10[\text{s}], 25[\text{m}])$
  - Point 3 in database
    - $(H_S^{DB}, T_P^{DB}, h^{DB}) = (9.37[m], 12.5[s], 39.1[m])$
  - $Fr = \frac{L}{gT^2} = \text{Fr}^{DB} \Rightarrow \lambda = \frac{h}{h^{DB}} = 0.64 \Rightarrow \begin{cases} u = u^{DB}\sqrt{0.64} \\ a = a^{DB} \end{cases}$

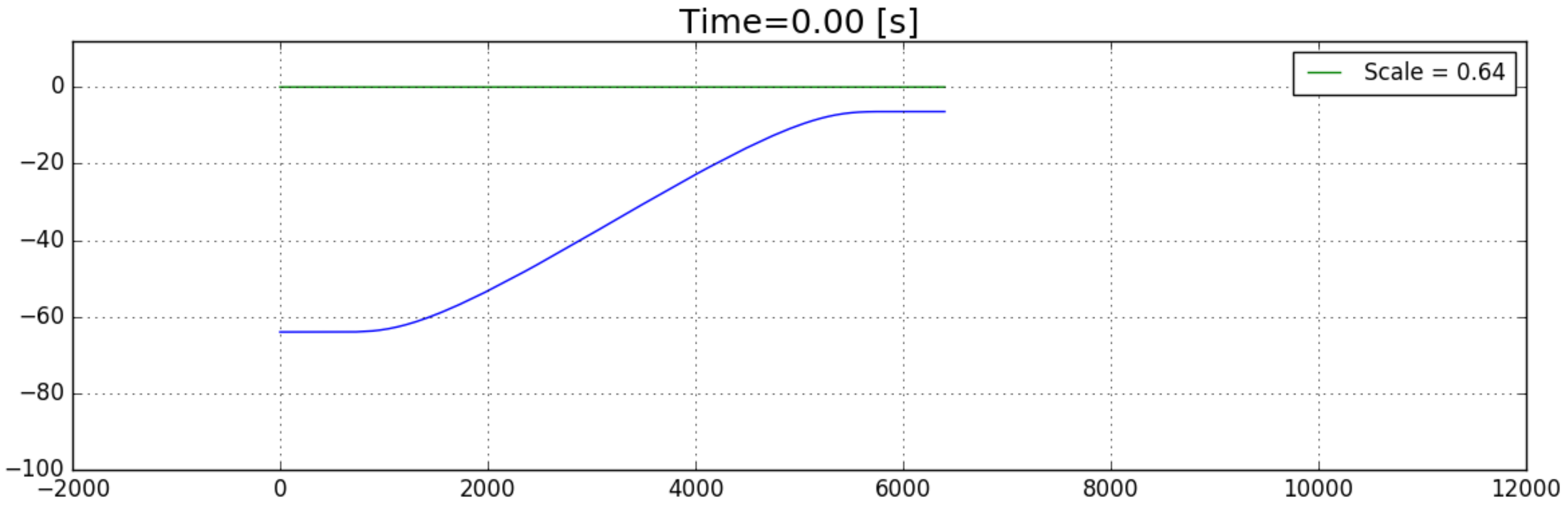


Proof of concept: Froude scaling
Perfectly scaled computational domains

- Domain Scale = 1
- Wave Scale = 1
- (Nx,Ny,Nz) = (8193,1,17)



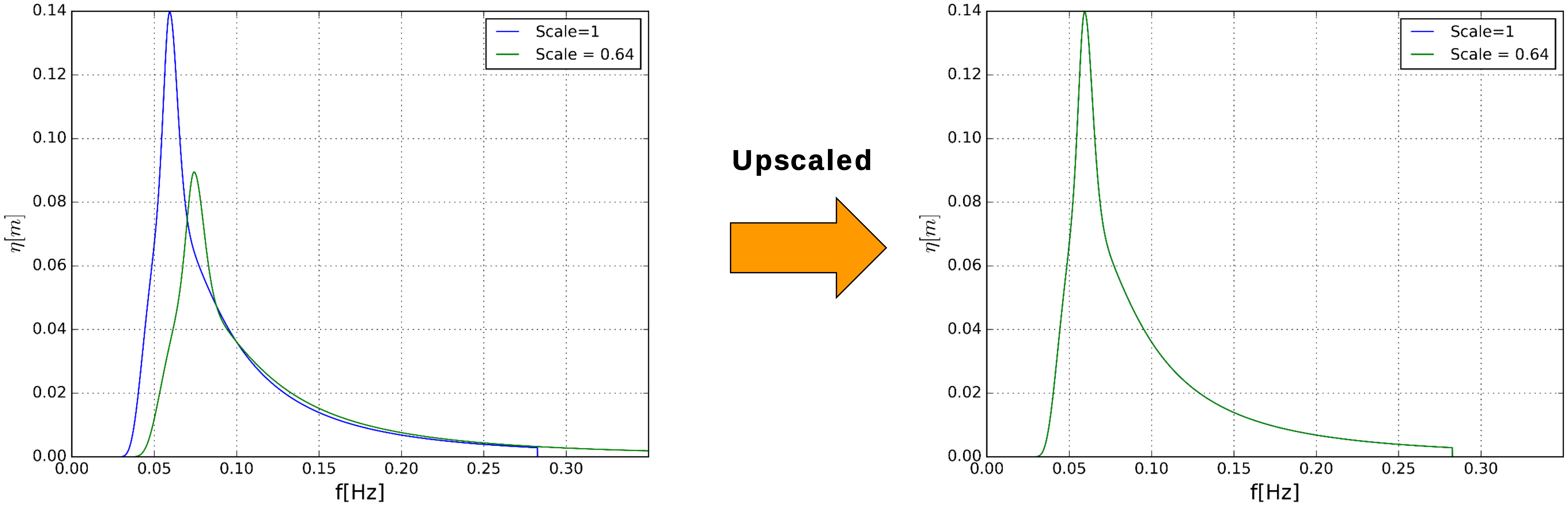
- Domain Scale = 0.64
- Wave Scale = 0.64
- (Nx,Ny,Nz) = (8193,1,17)



Proof of concept: Froude scaling
Input spectra

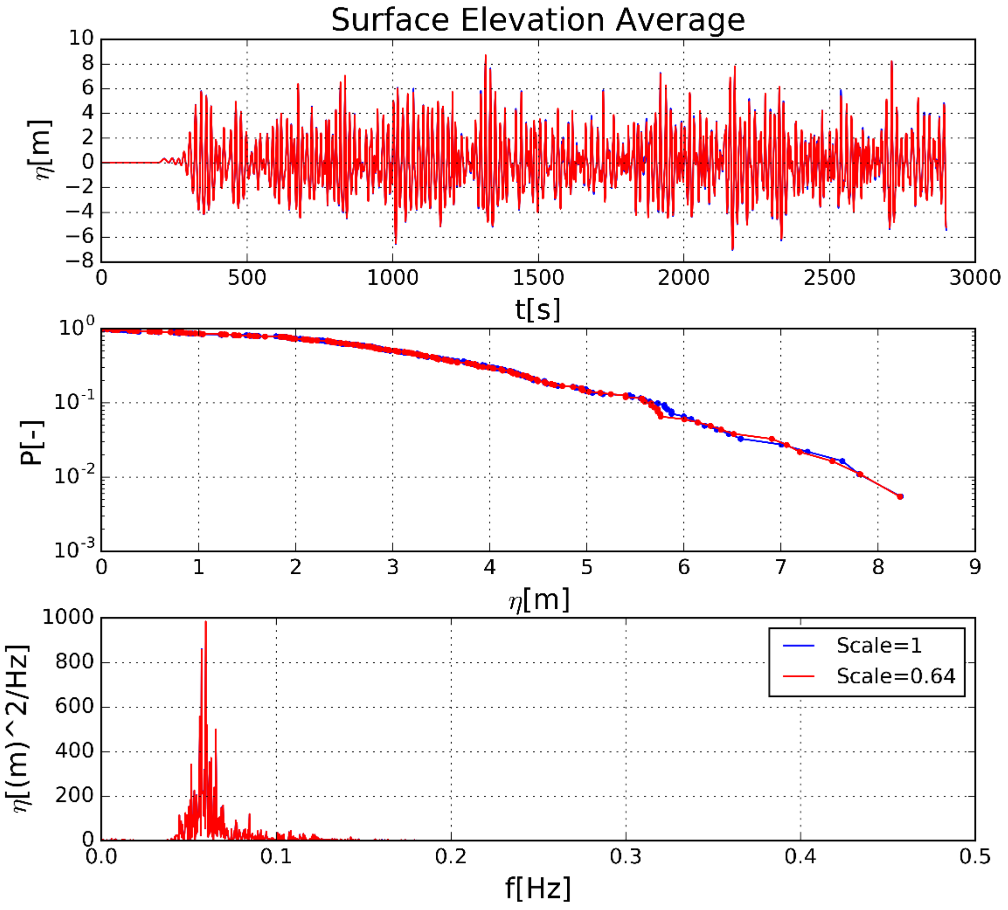
Wave Scale= 1 -> Hs = 8.84 [m]; Tp=16.85 [s]

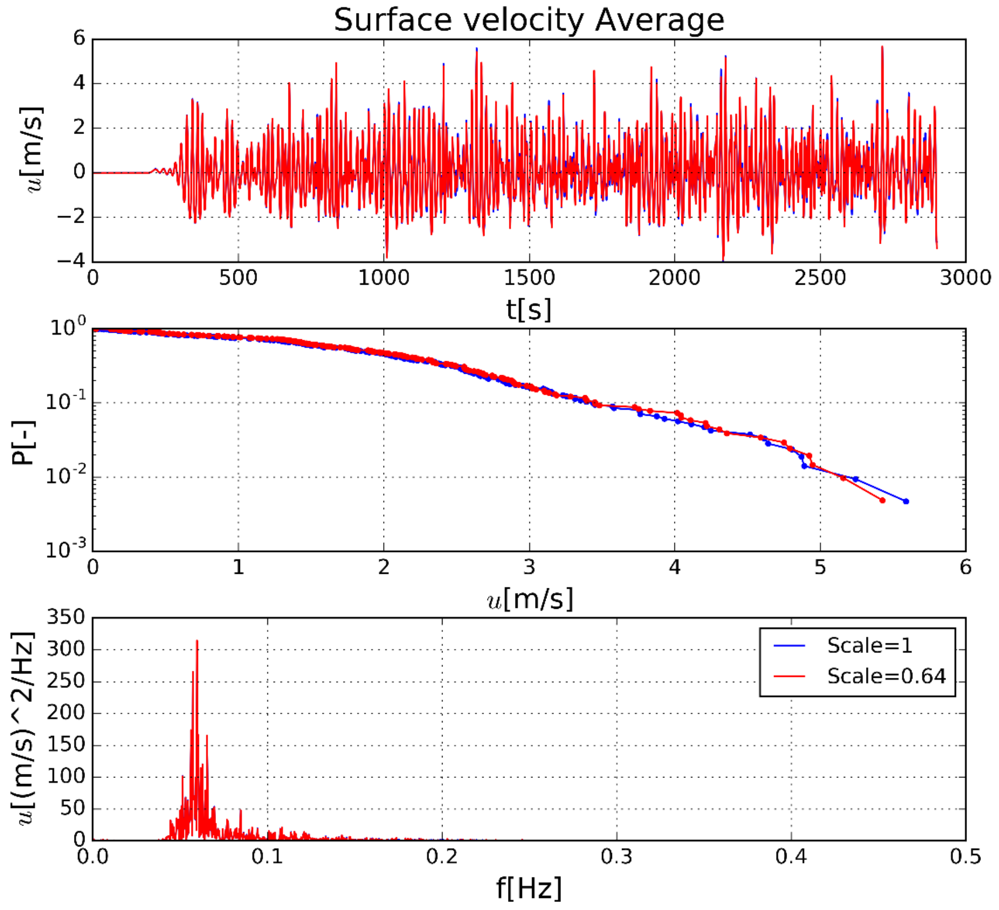
Wave Scale = 0.64 -> Hs = 5.66 [m]; Tp=13.48 [s]



Proof of concept: Froude scaling surface elevation (upscaled)

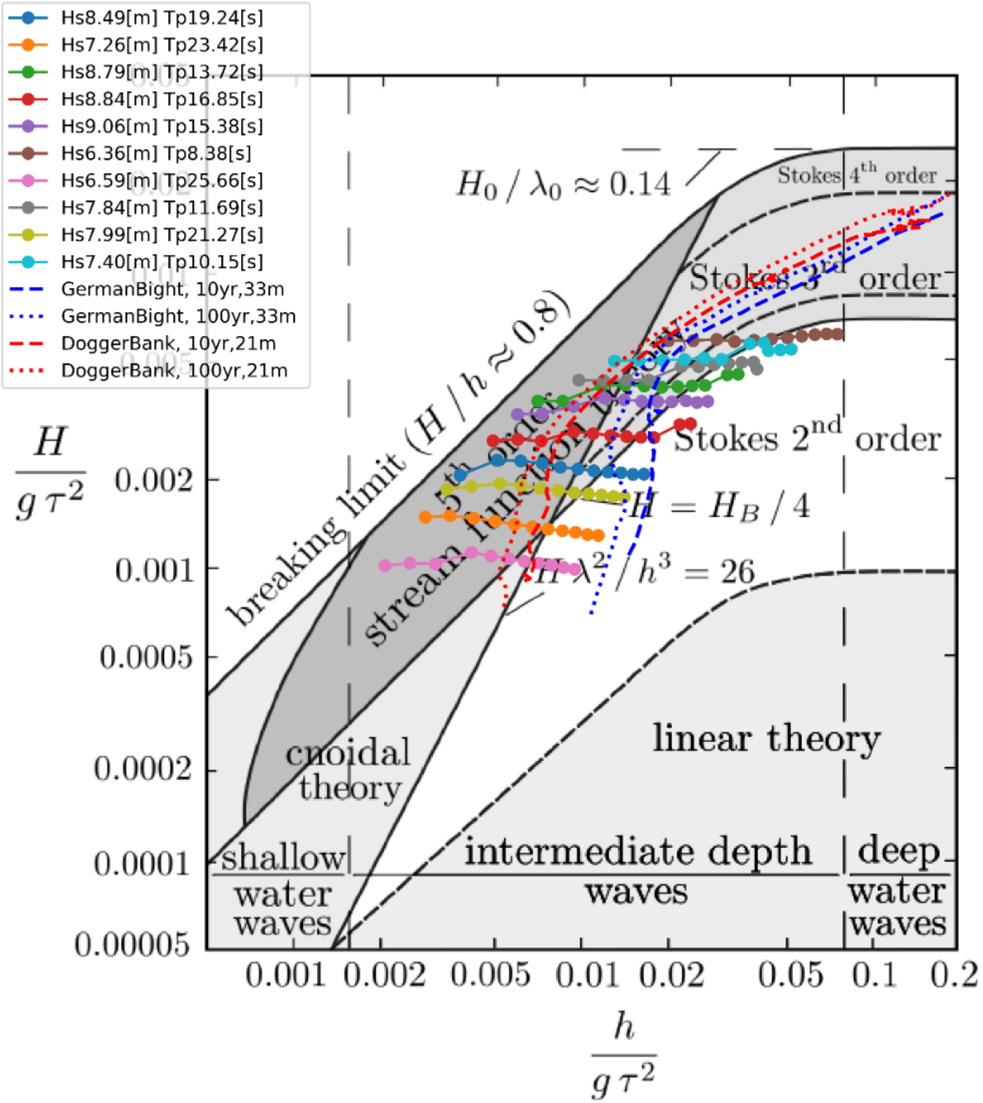
Proof of concept: Froude scaling surface elevation h=40m (upscaled, statistics)





Generation of the database: parameter space

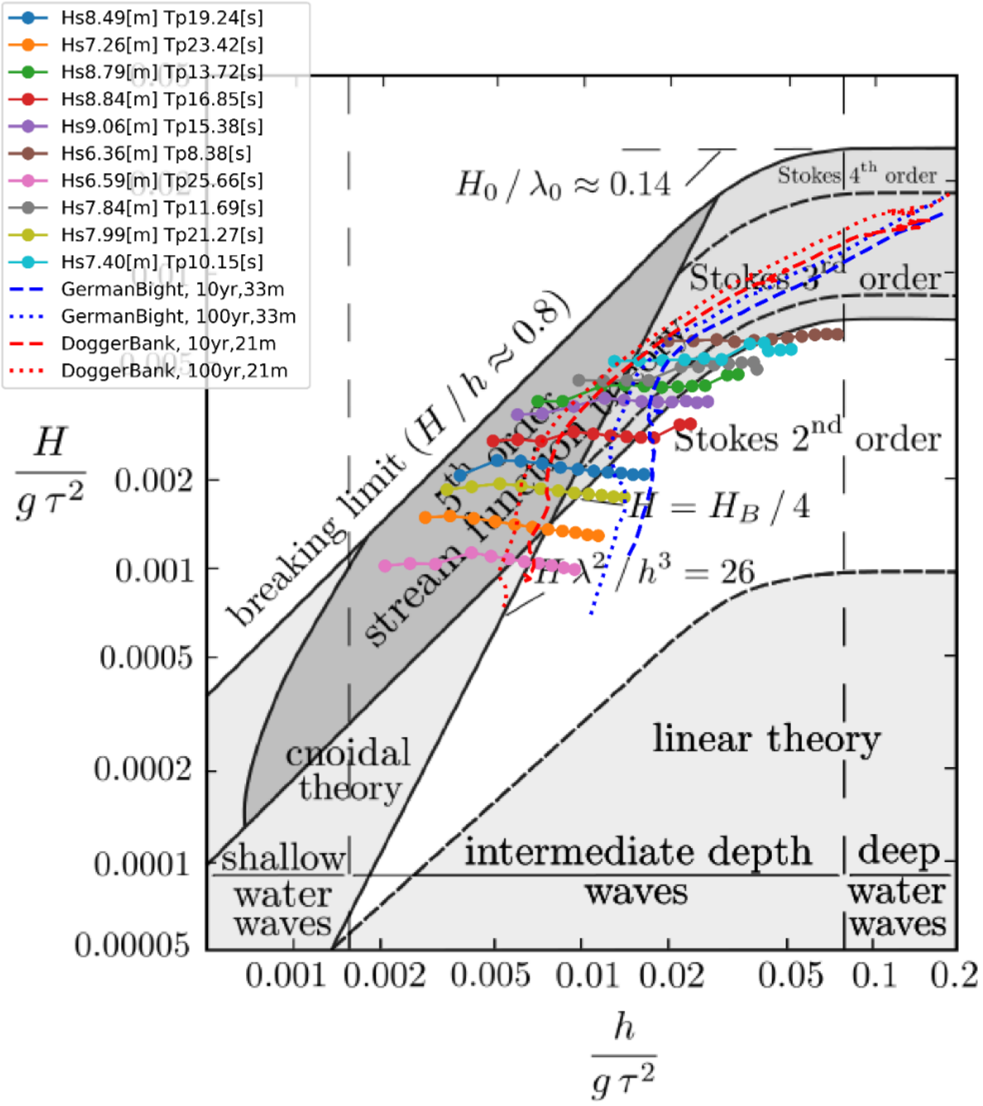
- Phisically:
  - Problem has three parameters
  - (H_S, T_P, h)
- Two are removed by using:
  - Froude scaling
  - Sampling at different depths
- One parameter left
  - A family of runs at different H_S/gT_P^2



Generation of the database: parameter space

- In reality, there are two other ”hidden” parameters
  1. Breaking waves
  2. Wave generation depth

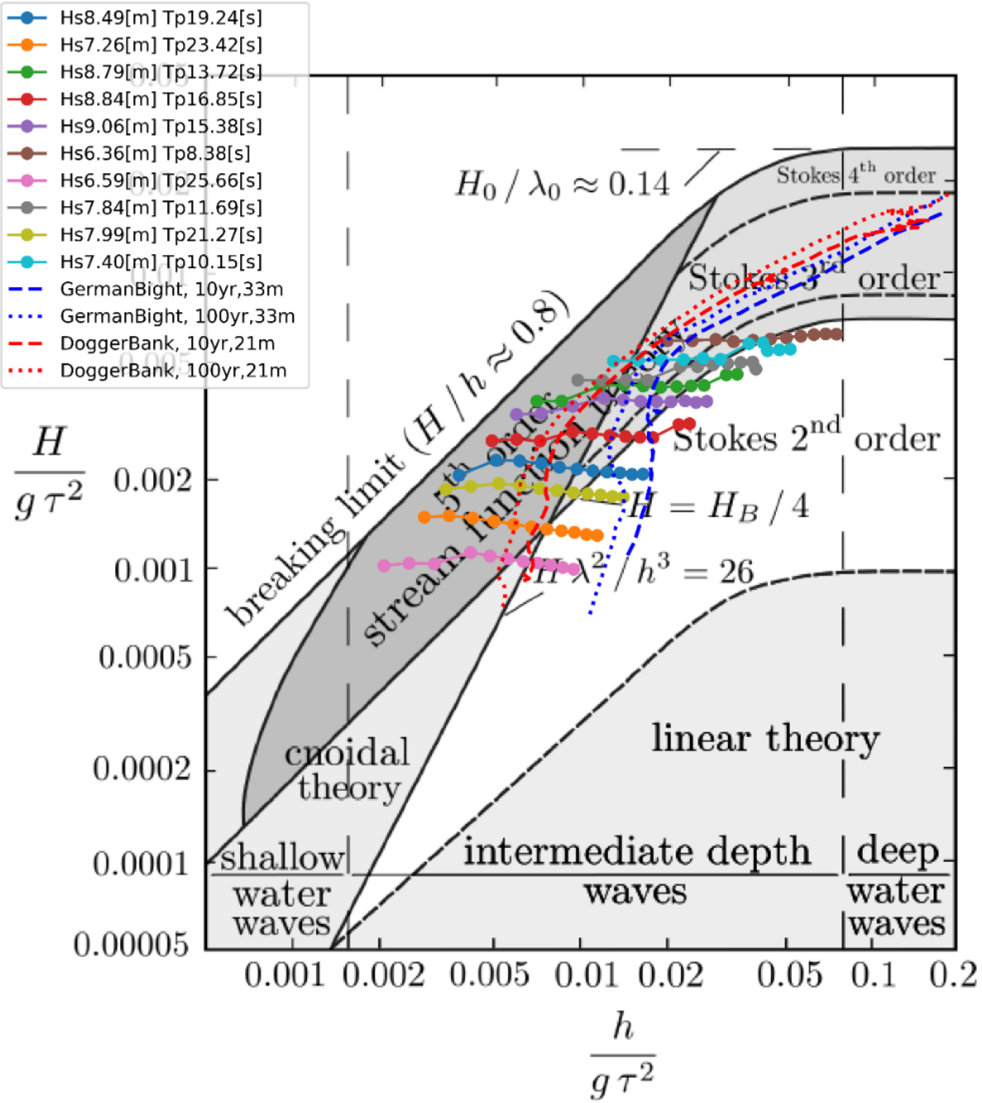
- Ideal conditions
  1. Handle the viscous breaking process via accurate models
  2. Start runs in deep water (all wave components $kh \geq 3$)



Generation of the database: parameter space

- In reality, there are two other "hidden" parameters
  1. Breaking waves
  2. Wave generation depth

- Current study
  1. Simplified breaking model: energy subtracted when the surface particle acceleration overcomes threshold value (Engsig-Karup et al. 2009)
  2. Choose the starting points carefully



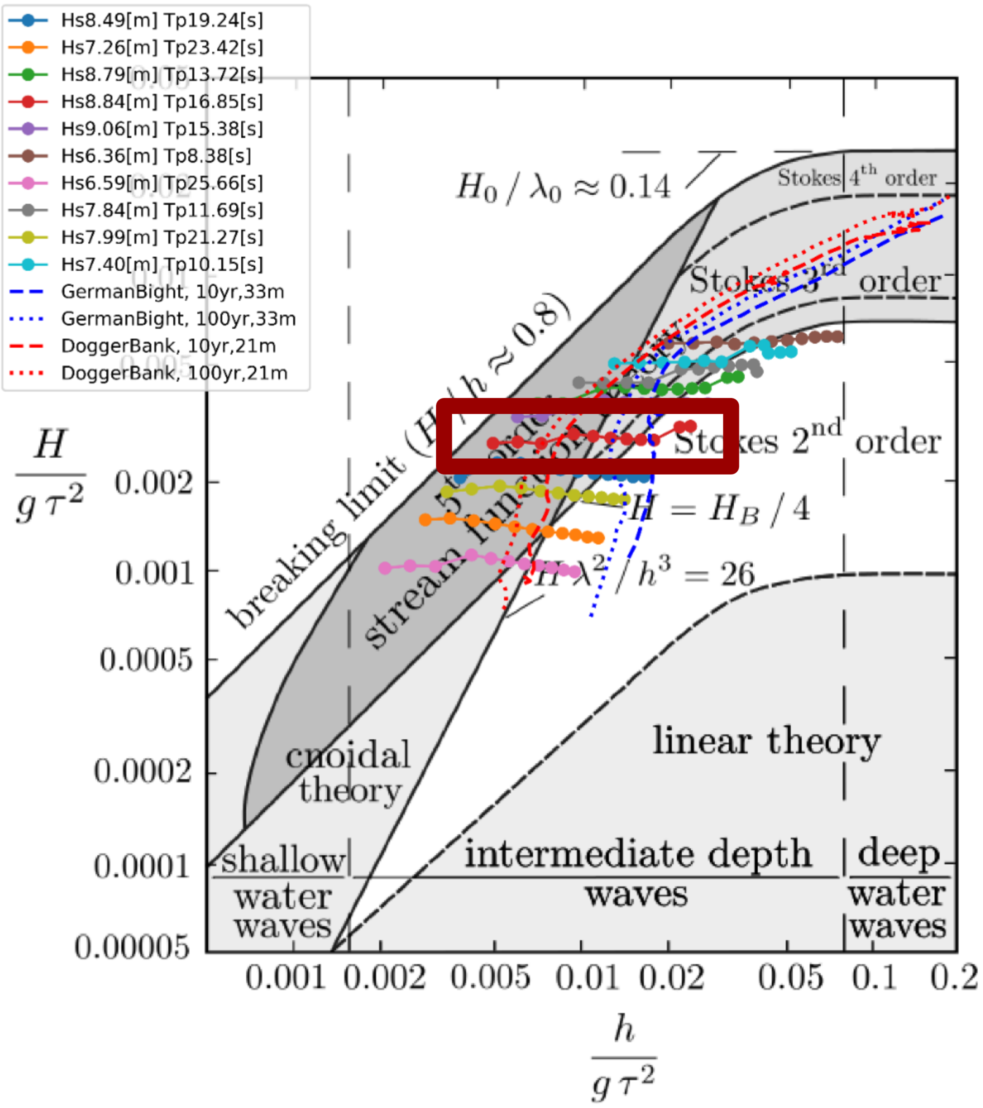
Wave generation depth: ”law of the short blanket”

- Generation depth: 100 [m]
  - $kh = 3 \rightarrow k = 0.03$
  - $\lambda = 210\,[m] \;\rightarrow T = 11\,[s] \rightarrow 0.091\,[Hz]$

- Part of the spectrum is not in deepwater

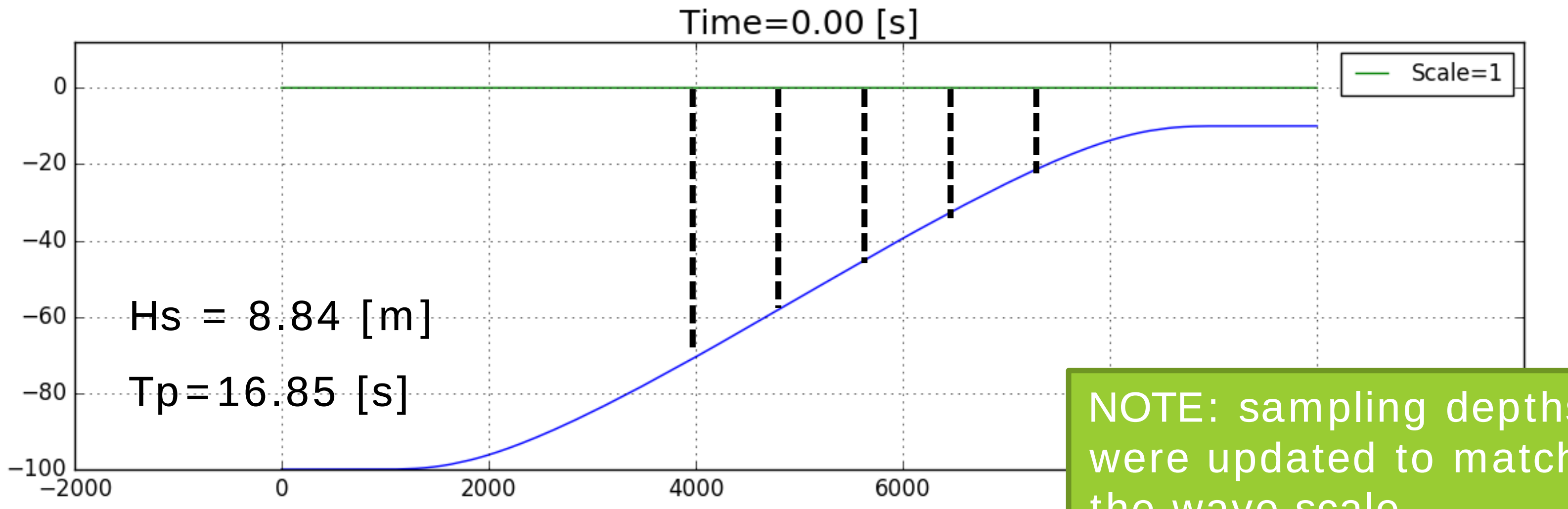
- To generate all waves in deep water:
  - Very short waves -> high grid resolution
  - Very long waves –> make the domain deeper (longer slope)

- *What consequences does it have?*
  - *Statistically speaking*



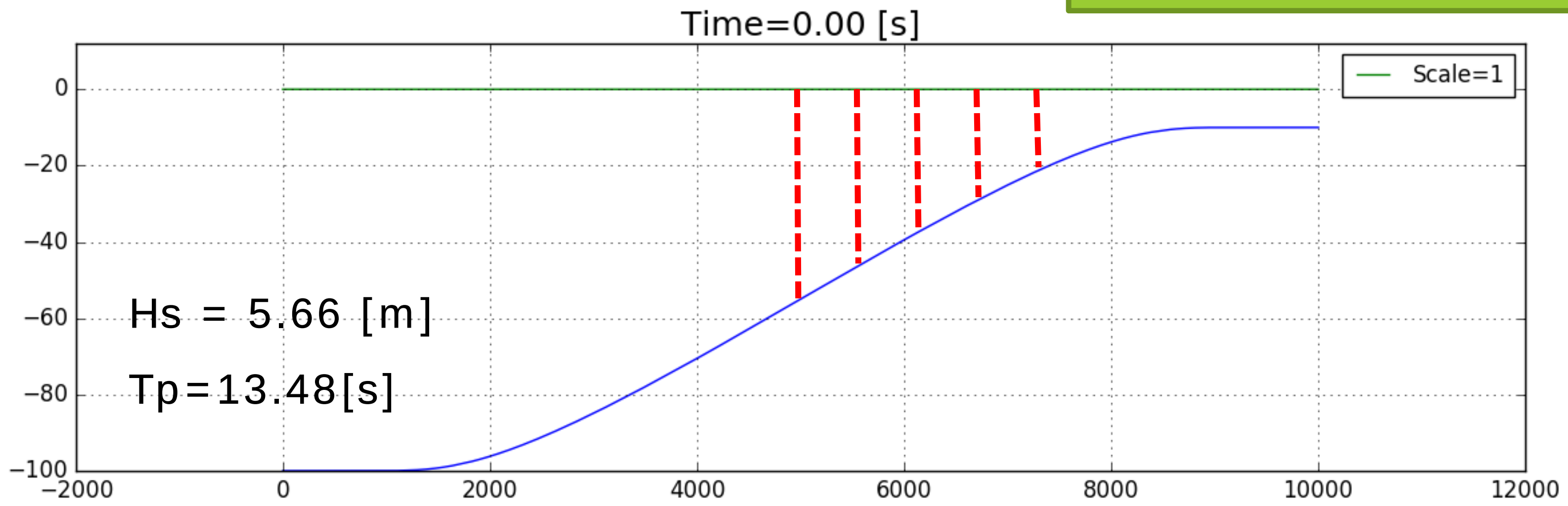
Generation of the database: wave generation depth

- Domain Scale = 1
- Wave Scale = 1



NOTE: sampling depths were updated to match the wave scale

- Domain Scale = 1
- Wave Scale = 0.64



Generation of the database: wave generation depth

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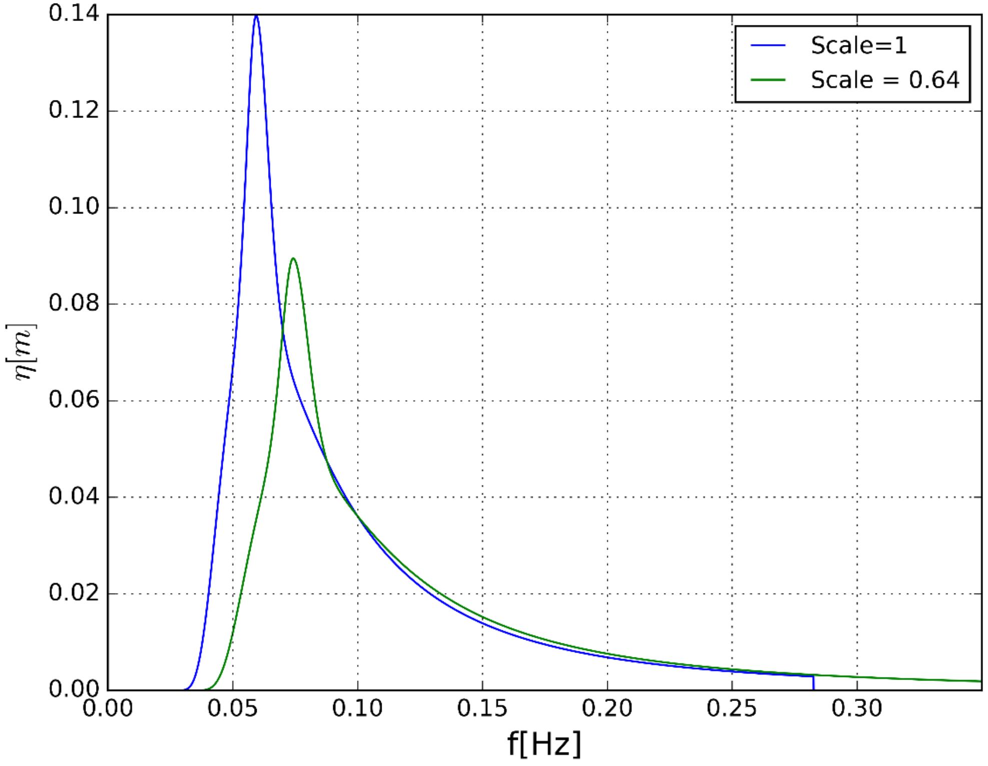
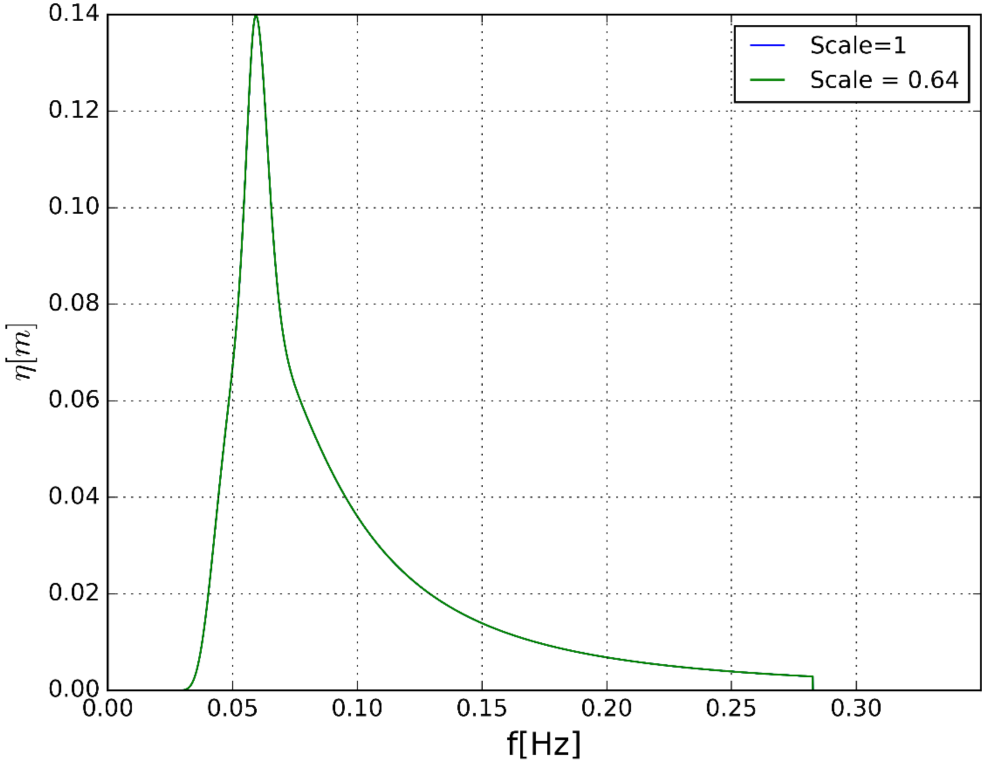


Upscaled

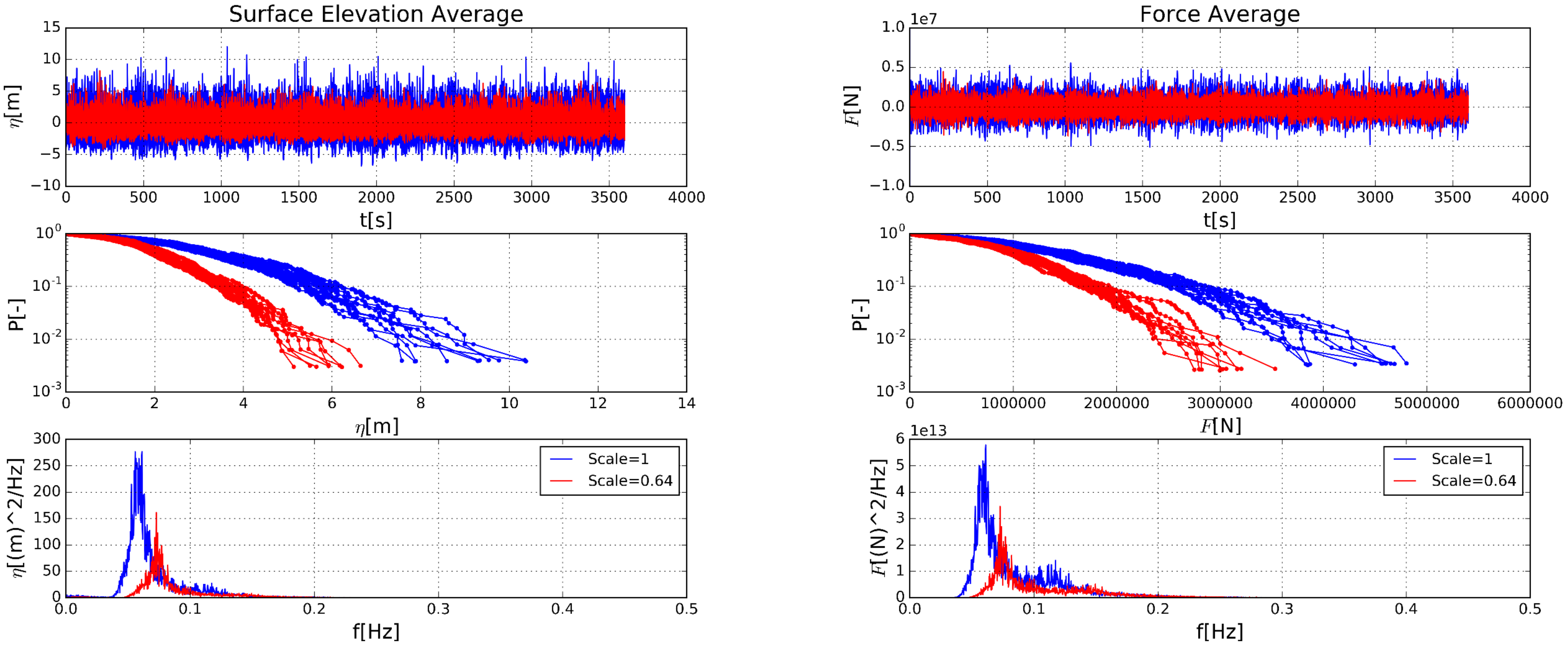


Froude Scaling of database: unscaled results

Hs = 8.84 [m]

Tp=16.85 [s]

h=30[m]



Froude Scaling of database: scaled results

Hs = 8.84 [m]

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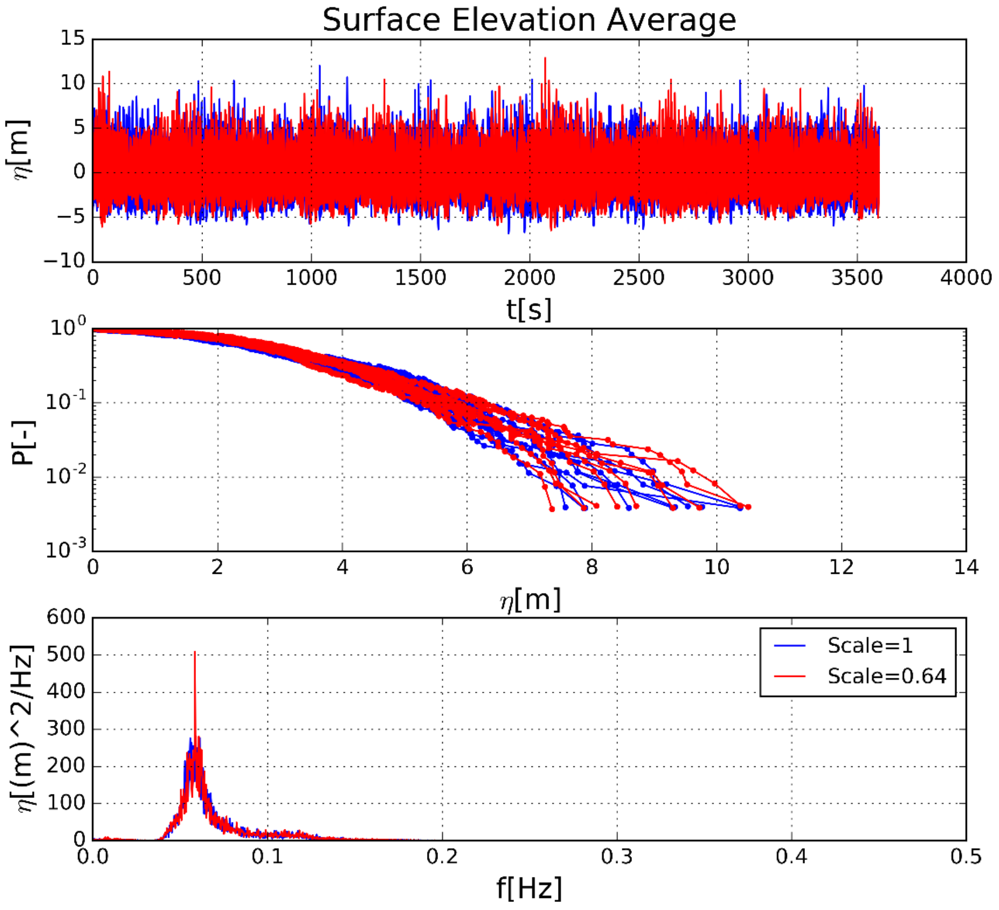
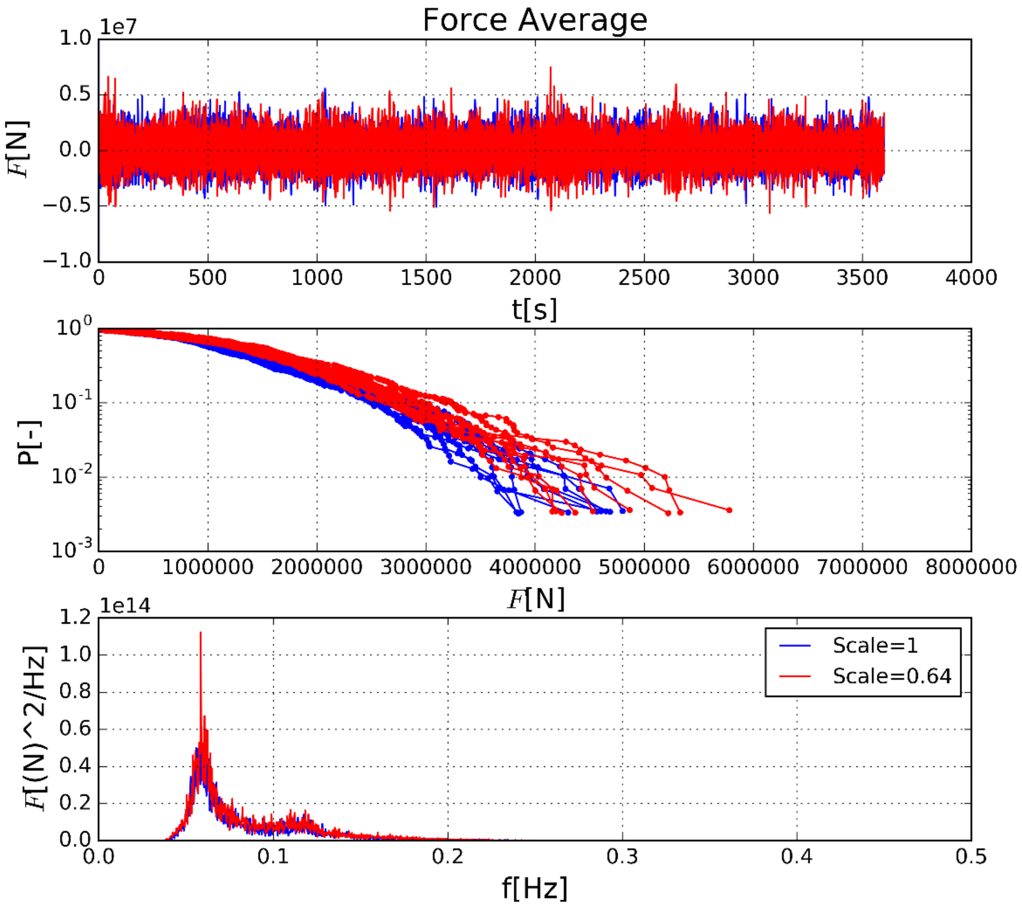
h=30[m]





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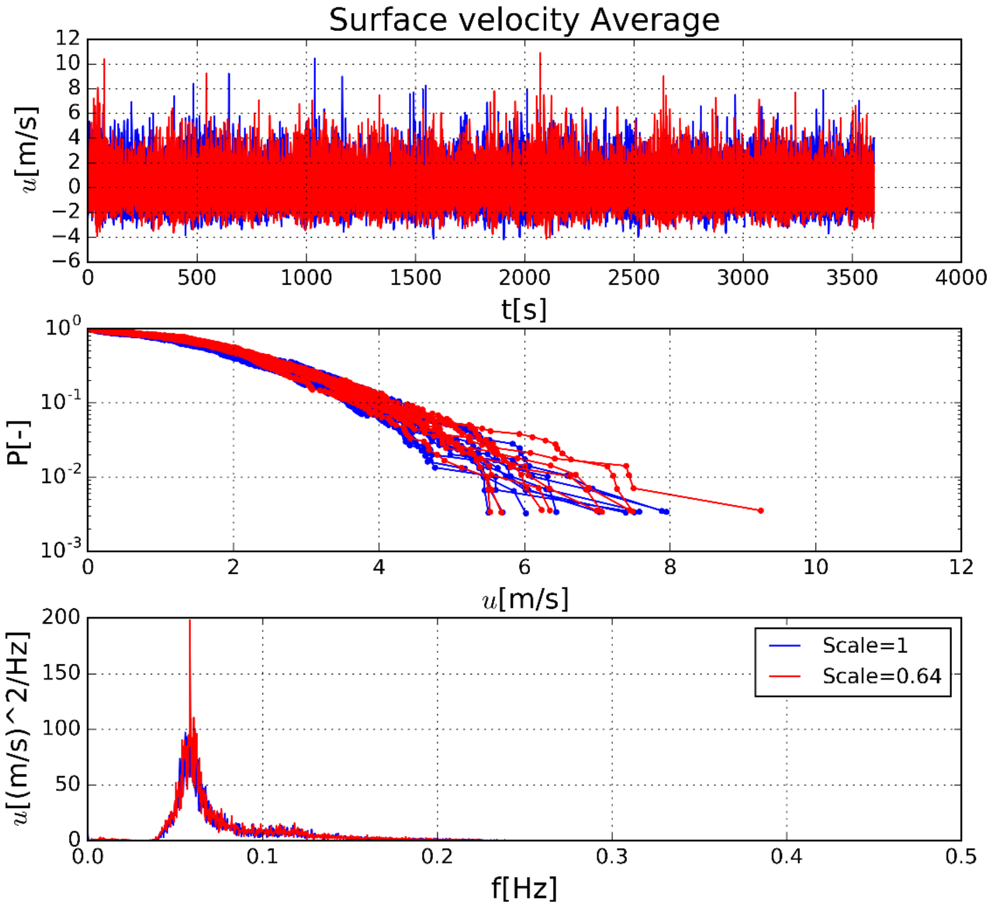

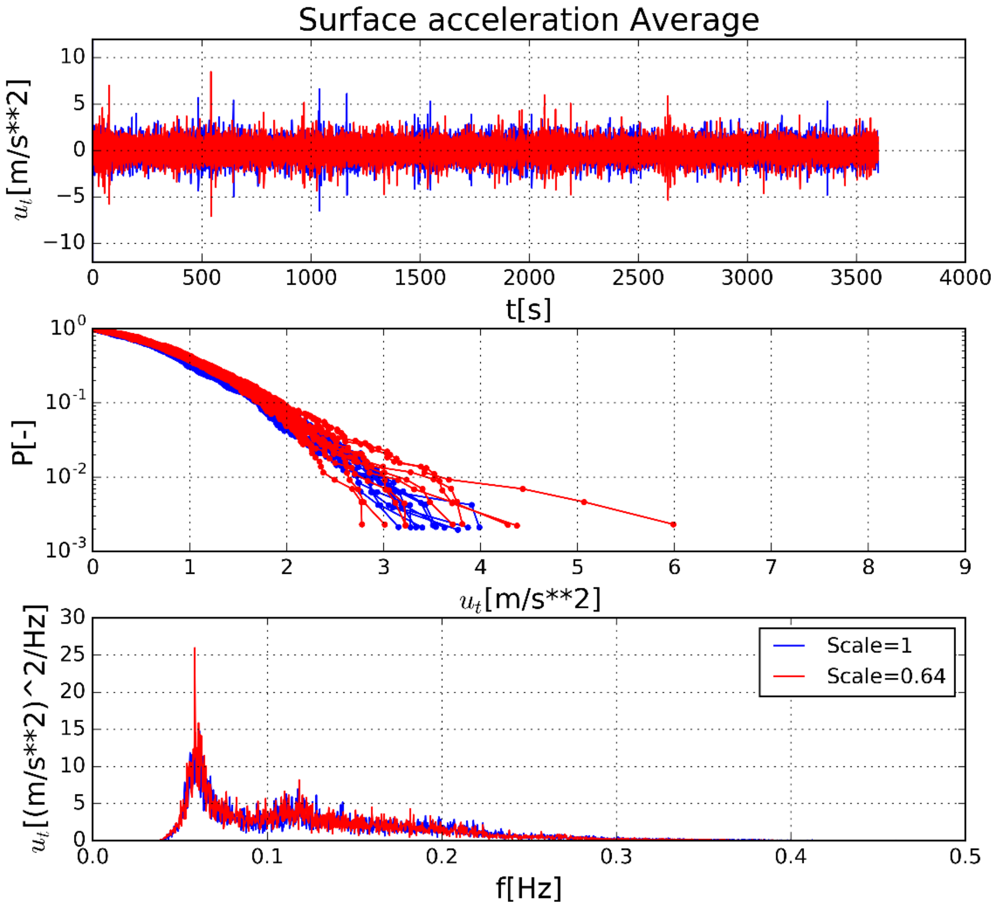

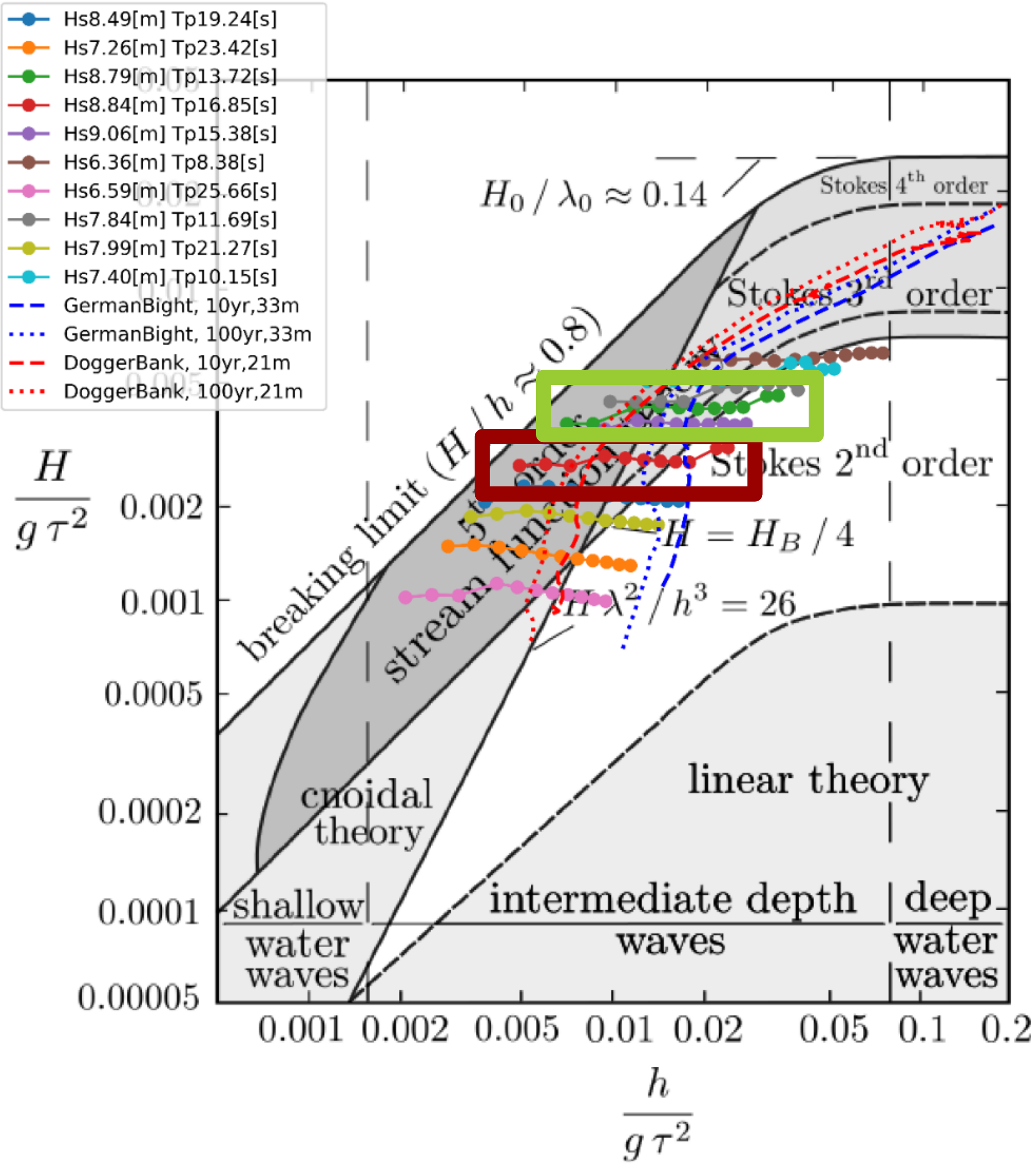

Hs = 8.79 [m]

Tp=13.72 [s]

h=30[m]

Hs = 8.84 [m]

Tp=16.85 [s]

h=30[m]

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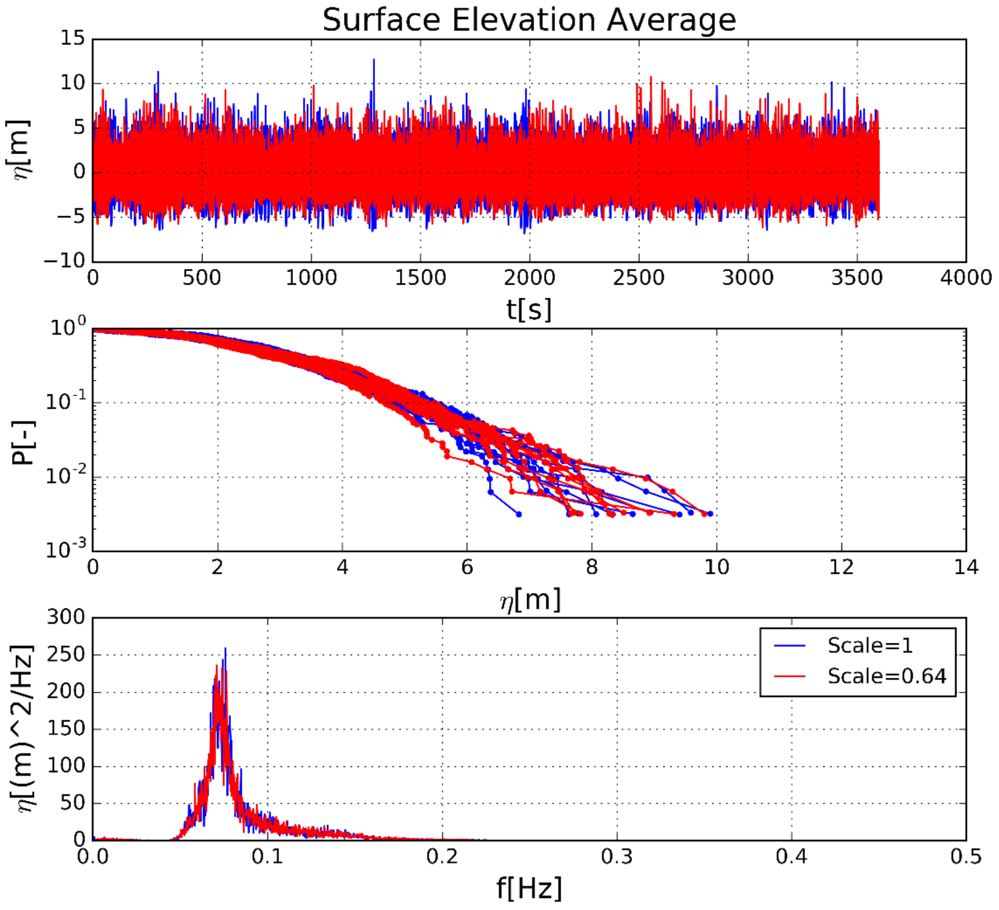

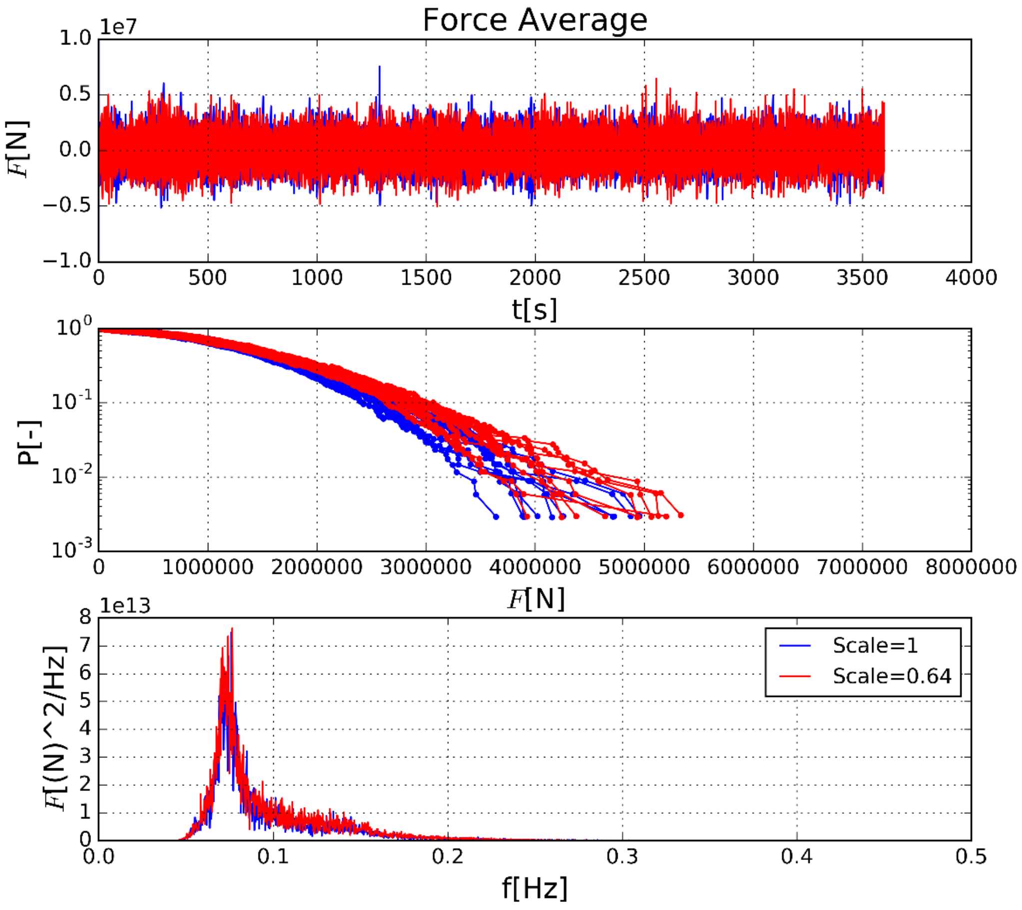

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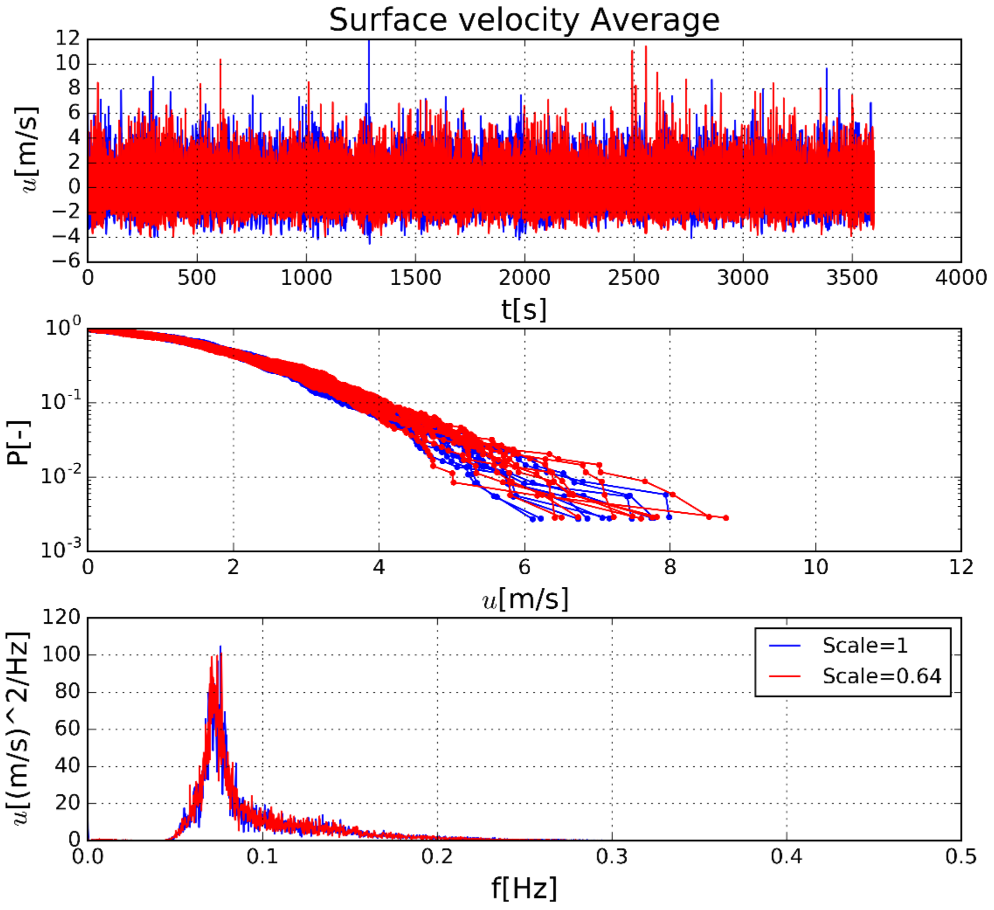

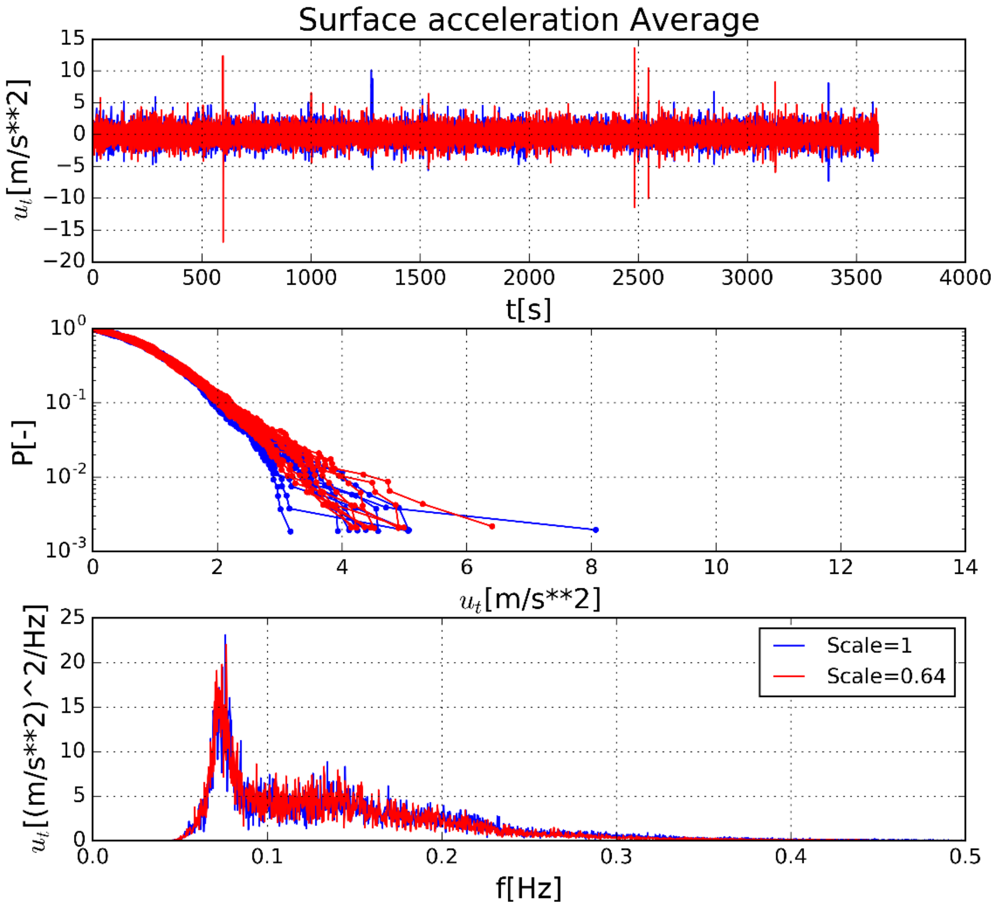

Conclusions

- The DeRisk database gives a practical way of calculating extreme loads on offshore wind turbines
  - Handles stochasticity and nonlinearity
- The validity of the database can be extended via Froude scaling
  - We verified Froude scaling is respected
- Identified limitations relative to the simplified parameter space
  - Offshore boundary condition must respect sufficiently high kh

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