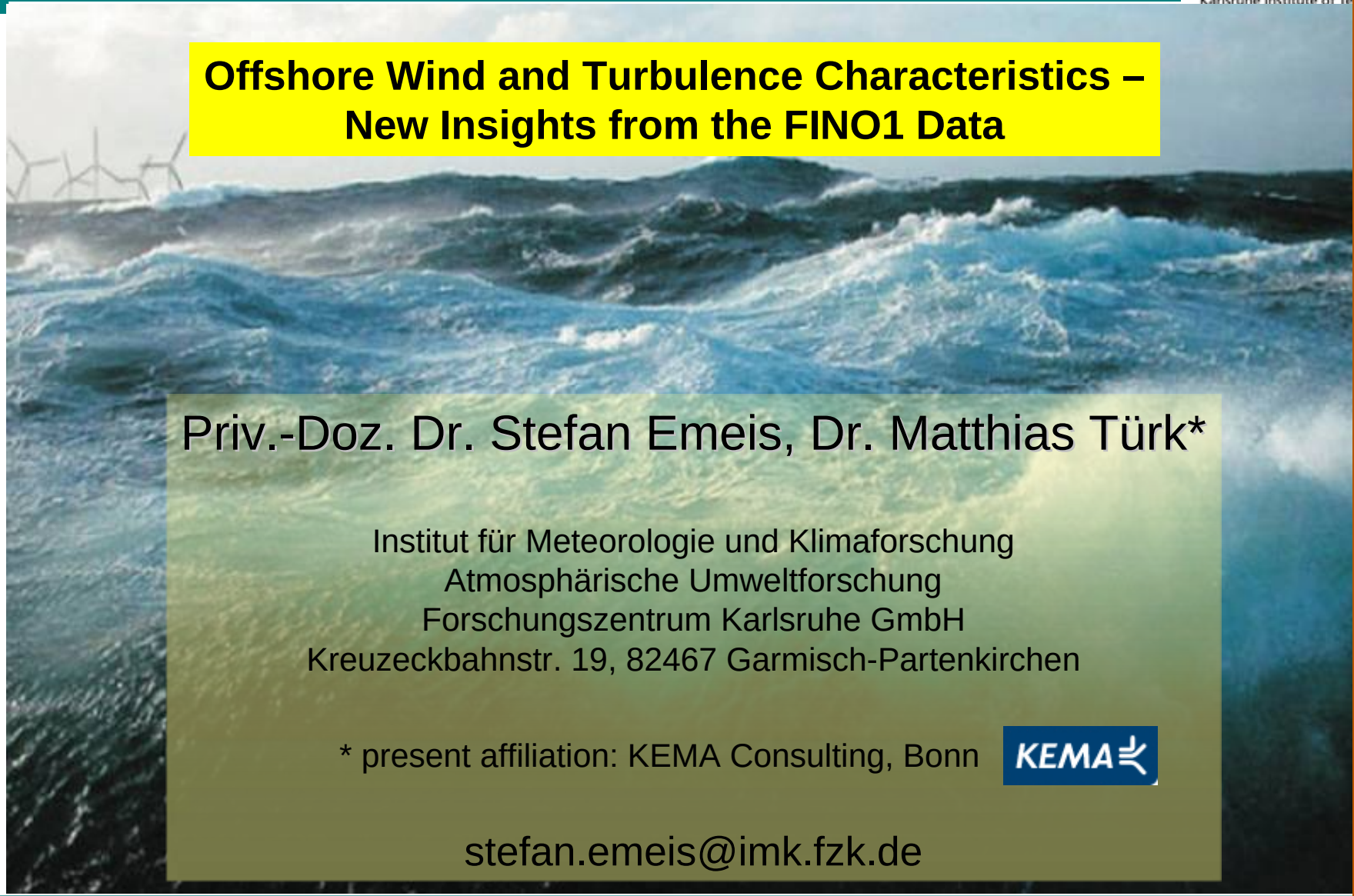
# Offshore Wind and Turbulence Characteristics – New Insights from the FINO1 Data



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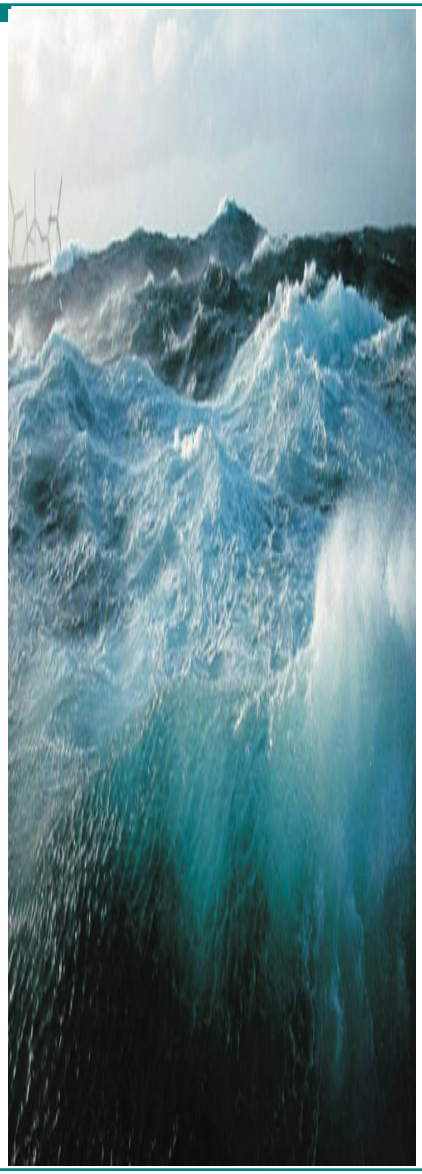

# Offshore wind and turbulence

**- sea surface horizontally homogeneous, smoother than onshore**

**but**

**- roughness is wind speed dependent**
**- roughness elements are moving**
**- thermal conditions: annual instead of diurnal variation**

## thus:

**- different vertical structure of the boundary layer**
**- different wind conditions**
**- different turbulence conditions**

**- wave age is additional scaling parameter**

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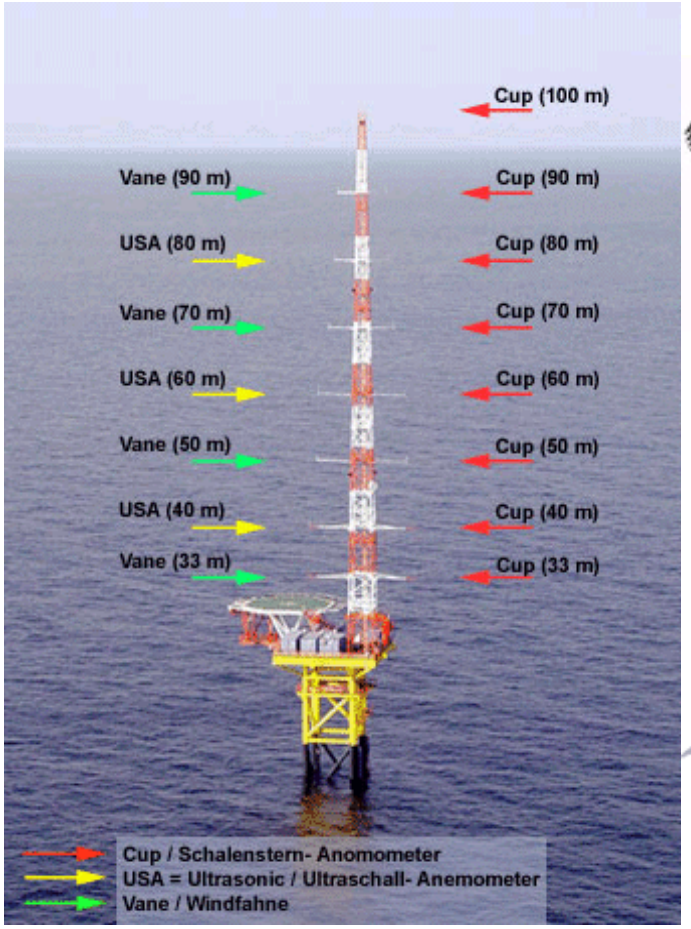
## data source:




## Project OWID

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Projektträger des BMBF, BMWA und BMU
Forschungszentrum Jülich GmbH

DEWI

ENERCON

GE Wind Energy

DEWI OCC

AREVA Multibrid

REpower Systems

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# wave height, vertical structure of the marine boundary layer and wave age

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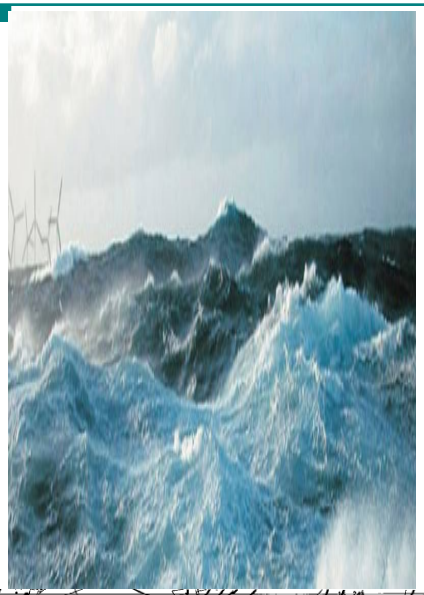
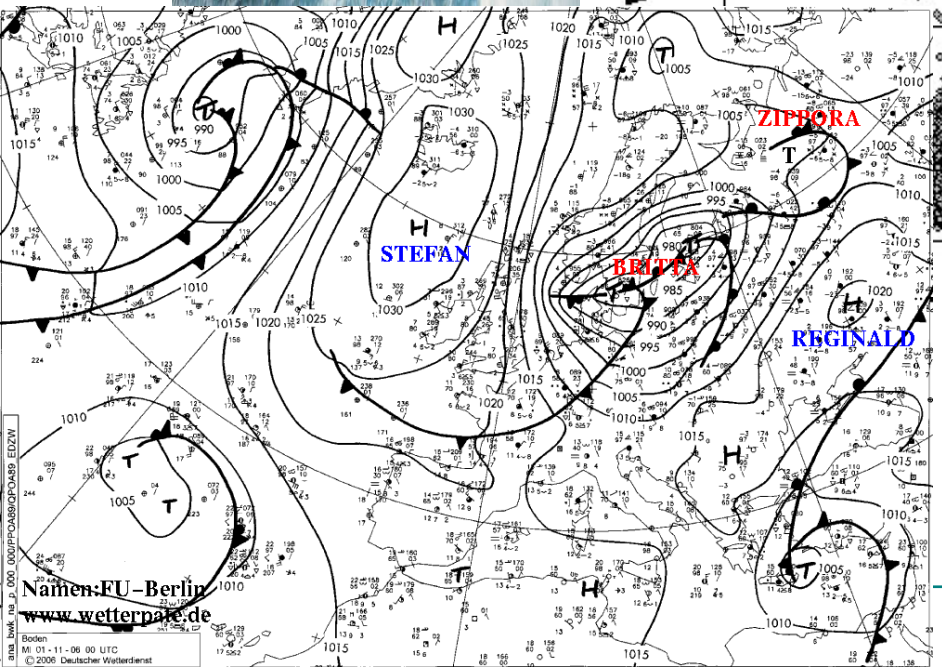
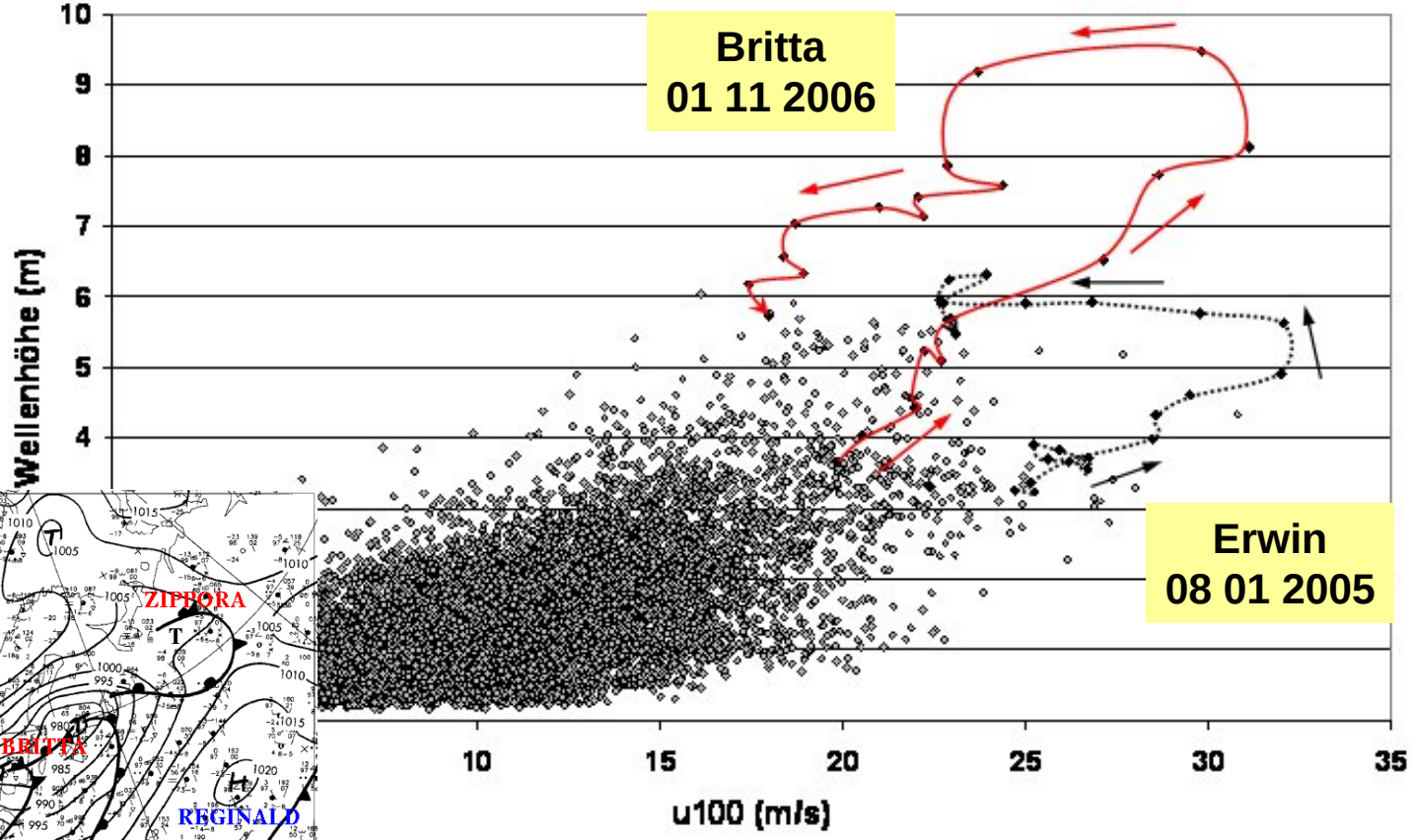
Karlsruhe Institute of Technology

# wave height as function of wind speed



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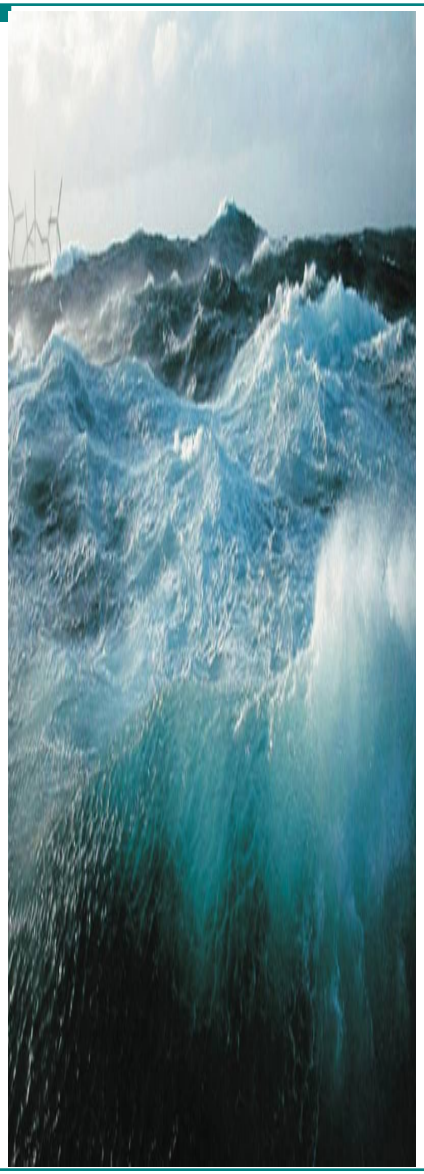
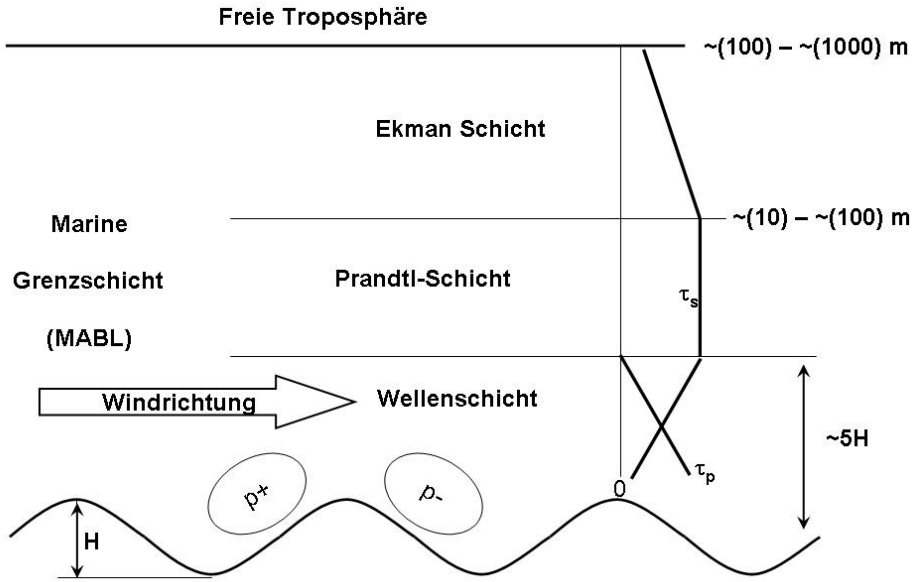


## wave and Prandtl layer height

| | | | |
|---|---|---|---|
| **wind speed** | **5 m/s** | **15 m/s** | **30 m/s** |
| **wave height** | **0,5 m** | **2 m** | **8 m** |
| **wave layer height** | **2,5 m** | **10 m** | **40 m** |
| **Prandtl layer height** | **10 m** | **40 m** | **100 m** |

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**wave age**

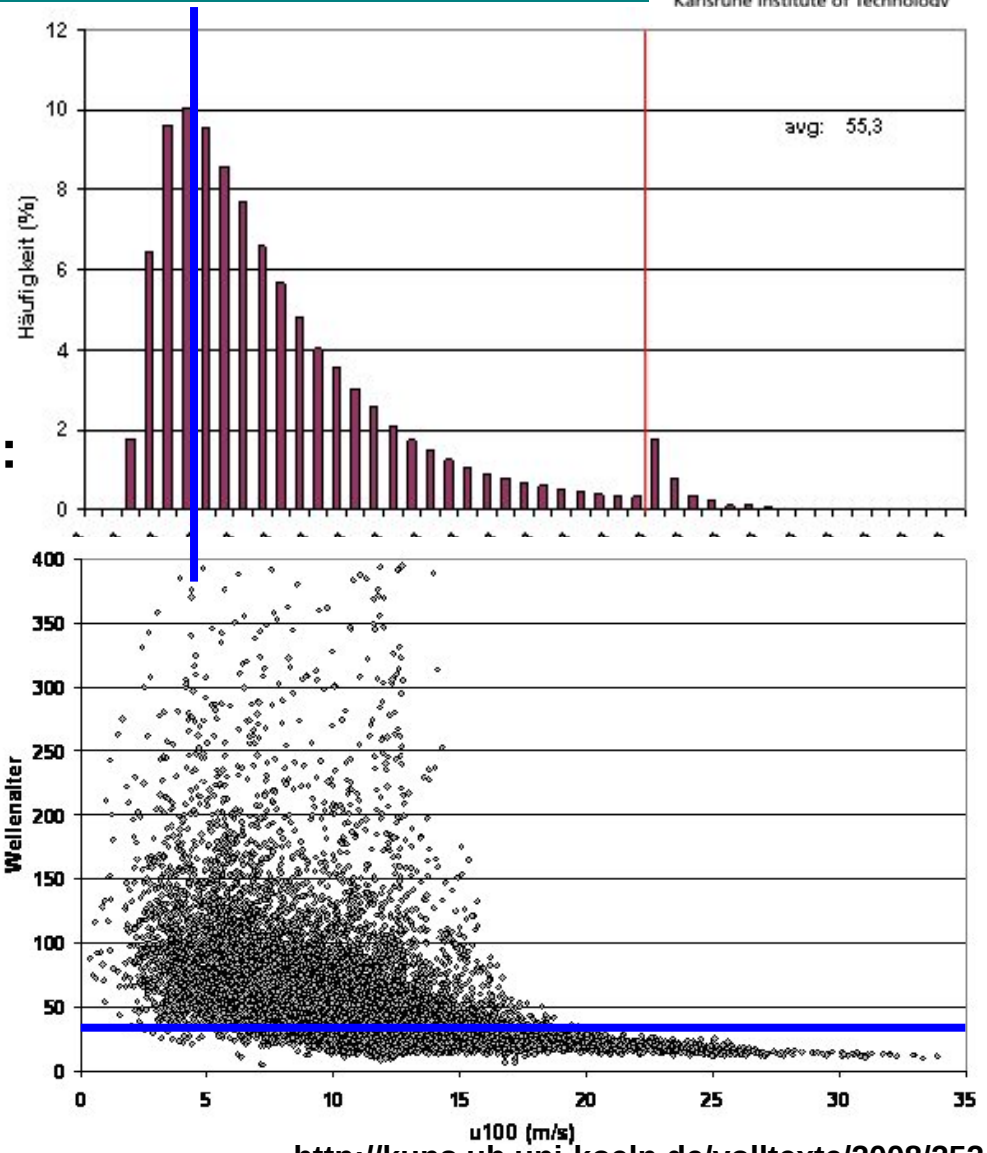
$u_*/c_{ph}$

**smaller than ~30:**

**wind driven, known PBL theories valid**

**larger than ~30**

**wave driven**

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# wind profiles and turbulence

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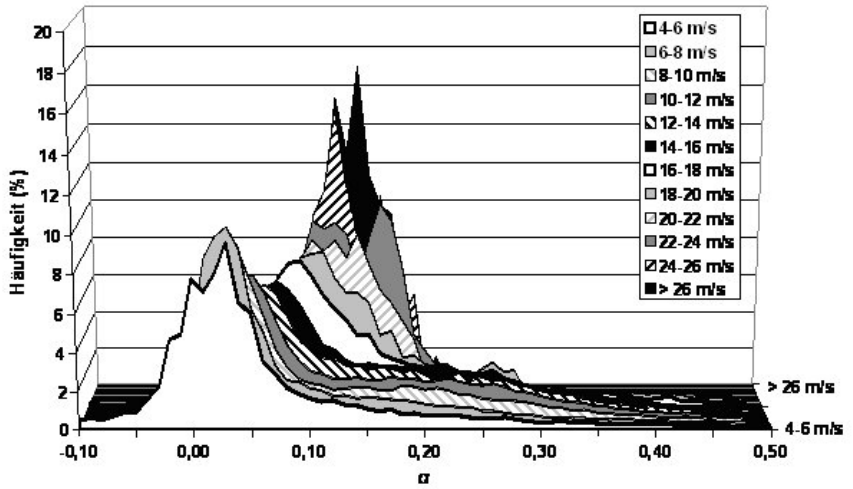
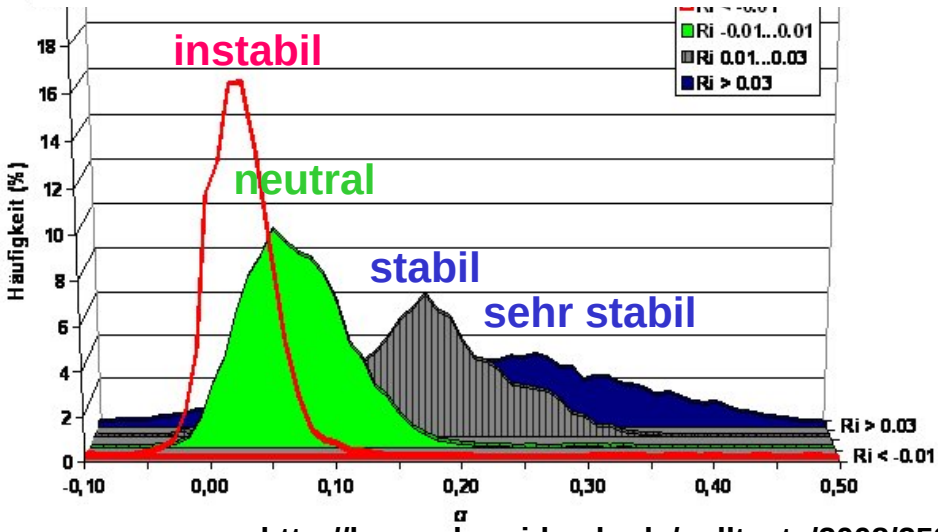
# exponent of power law

**as function of wind speed**

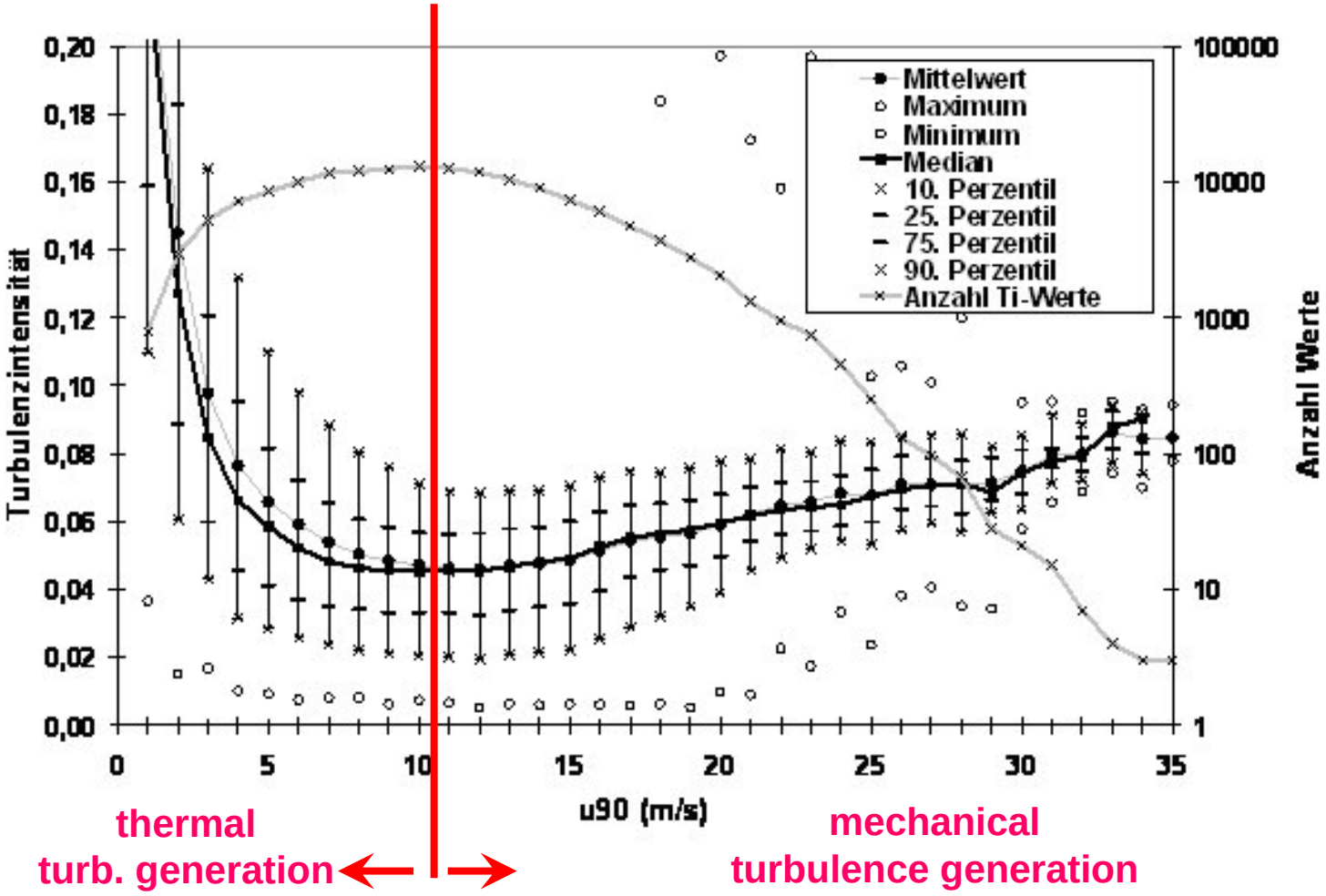



**as function of thermal stratification**




**http://kups.ub.uni-koeln.de/volltexte/2008/2524/**

# turbulence intensity as function of wind speed

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# Comparison with the assumptios made in IEC 61400-1 and 61400-3

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# Normal wind profile model (NWP)

## The IEC 61400-3 gives 0.14 for the power-law exponent

## Evaluation for $z_{ref}$ = 40 m, z = 90 m

| Wind speed (m/s) | Mean | Standard deviation | Number |
|---|---|---|---|
| **4-6** | 0,048 | 0,144 | 18178 |
| **6-8** | 0,068 | 0,114 | 23318 |
| **8-10** | 0,094 | 0,109 | 25236 |
| **10-12** | 0,116 | 0,109 | 24599 |
| **12-14** | 0,129 | 0,104 | 19863 |
| **14-16** | 0,137 | 0,101 | 13645 |
| **16-18** | 0,138 | 0,092 | 8540 |
| **18-20** | 0,142 | 0,084 | 4874 |
| **20-22** | 0,131 | 0,056 | 2270 |
| **22-24** | 0,133 | 0,039 | 1210 |
| **24-26** | 0,130 | 0,034 | 384 |
| **>26** | 0,130 | 0,025 | 247 |

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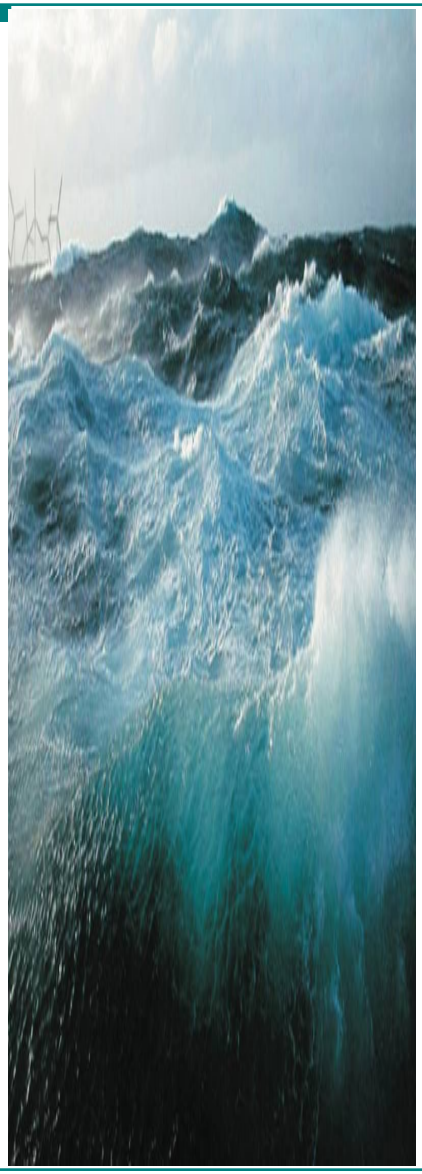

# Normal wind profile model (NWP)

**The IEC 61400-3 gives 0.14 for the power-law exponent**

**Evaluation for $z_{ref}$ = 40 m, z = 90 m**

| **Bulk-Richardson-Number $Ri_B$** | **Mean** | **Standard deviation** | **Number** |
|---|---|---|---|
| **< -0,01** | 0,023 | 0,036 | 9450 |
| **-0,01…0,01** | 0,063 | 0,048 | 11939 |
| **0,01…0,03** | 0,149 | 0,065 | 10626 |
| **> 0,03** | 0,190 | 0,185 | 11361 |

IEC 61400-3 does not seem to be sufficiently conservative in all cases.

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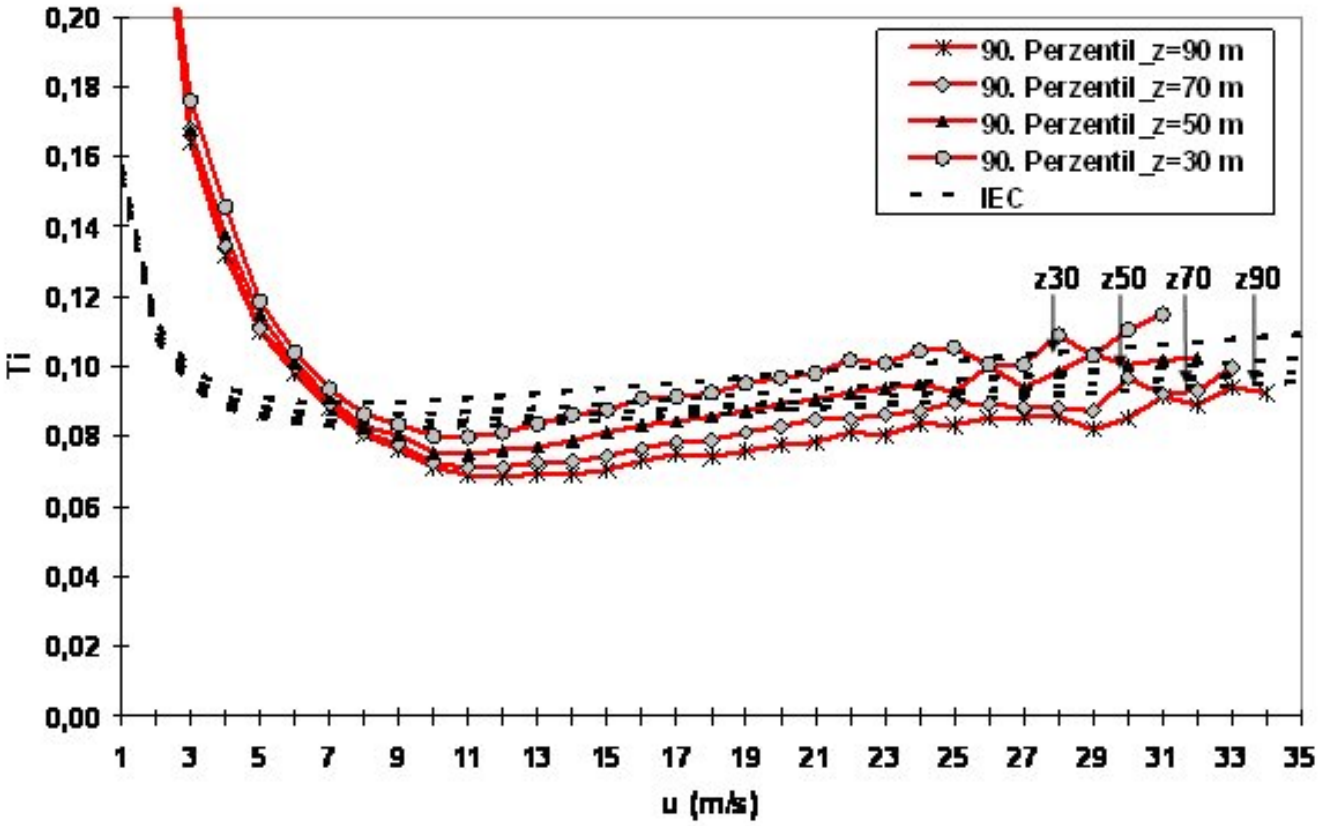
# Normal turbulence model (NTM)

## Comparison: observed and assumed by IEC-Norm
## 90-Percentiles of turbulence intensity




http://kups.ub.uni-koeln.de/volltexte/2008/2524/

# Normal turbulence model (NTM)

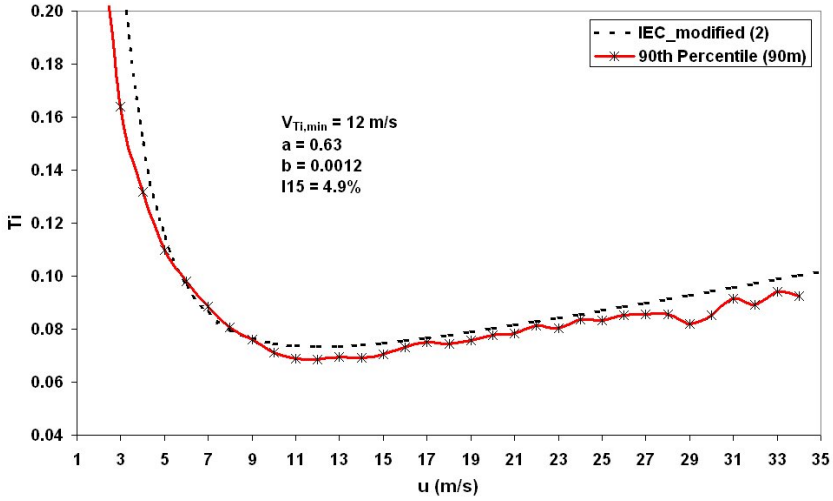
**IEC 61400-3 (Eq. 27) says:**

$$\sigma_{u,s} = \frac{V_{hub}}{\ln(z_{hub} / z_0)} + 1{,}28(1{,}44 m/s) I_{15}$$

**alternative proposal:**

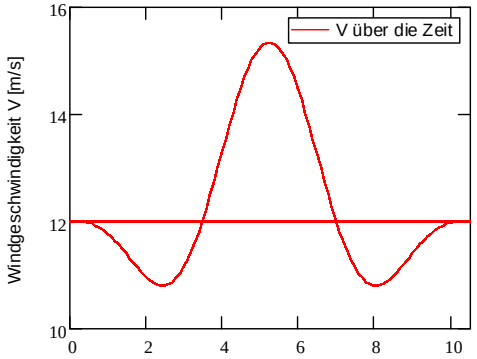
$$\sigma_{u,s} = a \frac{V_{hub}}{\ln(z_{hub} / z_0)} + \frac{2V_{Ti,\min}}{V_{hub}} (1{,}44 m/s) I_{15} + bV_{hub}$$

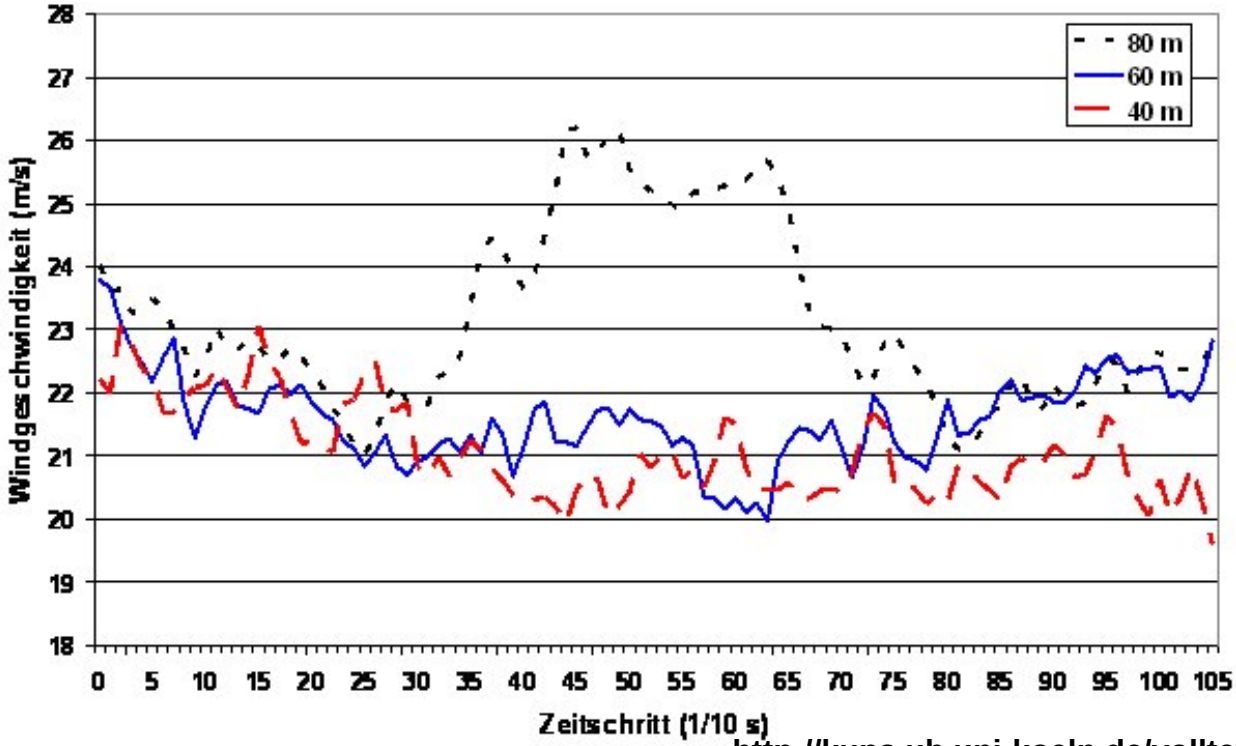
**with a = 0.63, b = 0.0012, $I_{15}$ = 4.9%,$V_{Ti,min}$ = 12 m/s for $z_{hub}$ = 90 m**



# Extreme operating gust (EOG)

**simultaneous observation in three heights (10,5 s), correlation > 0,85**

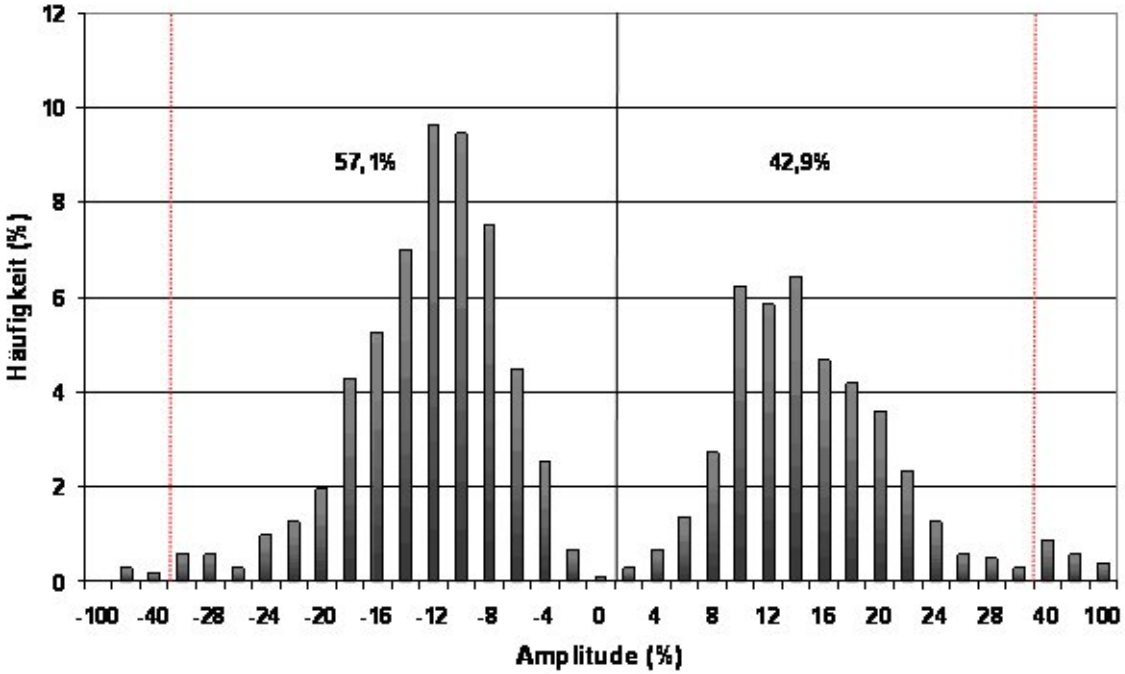



**http://kups.ub.uni-koeln.de/volltexte/2008/2524/**

# Extreme operating gust (EOG)

**frequency distribution of EOG (10,5 s) in 80m height (e.g. 440 cases in 2005)**




**http://kups.ub.uni-koeln.de/volltexte/2008/2524/**

**more negative as positive „Mexican hats“**

## Summary comparison to IEC 61400

**NWP: exponent 0.14 is not always conservative**

**NTM: Eq. (27) for $\sigma_u$ in IEC 61400-3 should be reformulated**

**EWM: Class II seems to be sufficient**

**EOG: - more negative than positive „hats“**
**- EOG with 8 s length 1.6 times more frequent than those with 10.5 s length**

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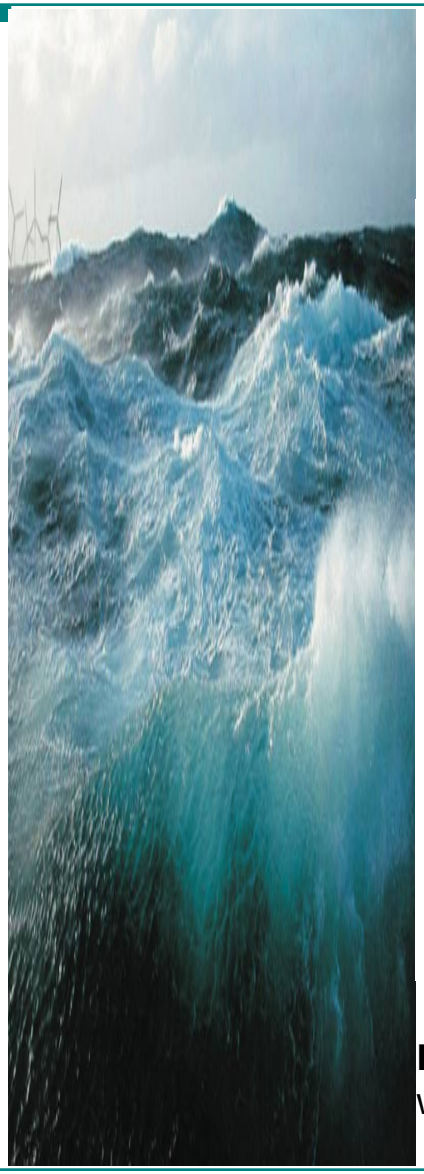
# Some final thoughts on offshore windparks with a simple analytical model



# momentum balance of a windpark in a turbulent flow (EF93-model)

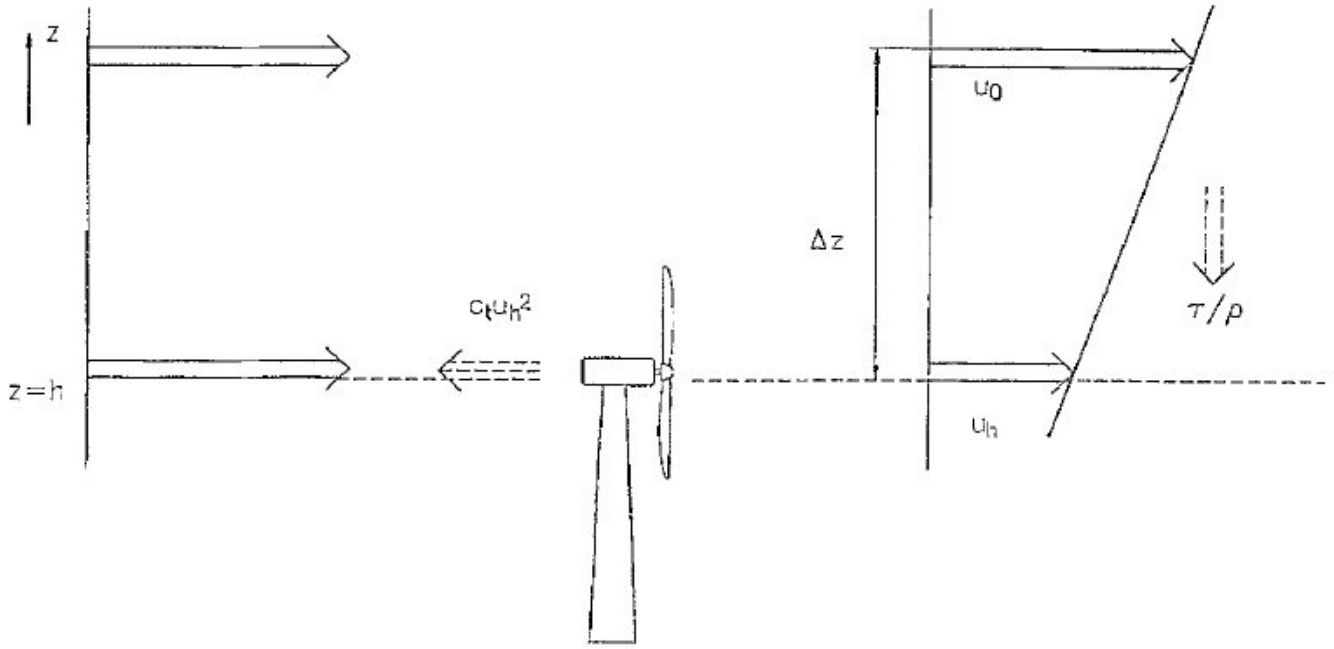
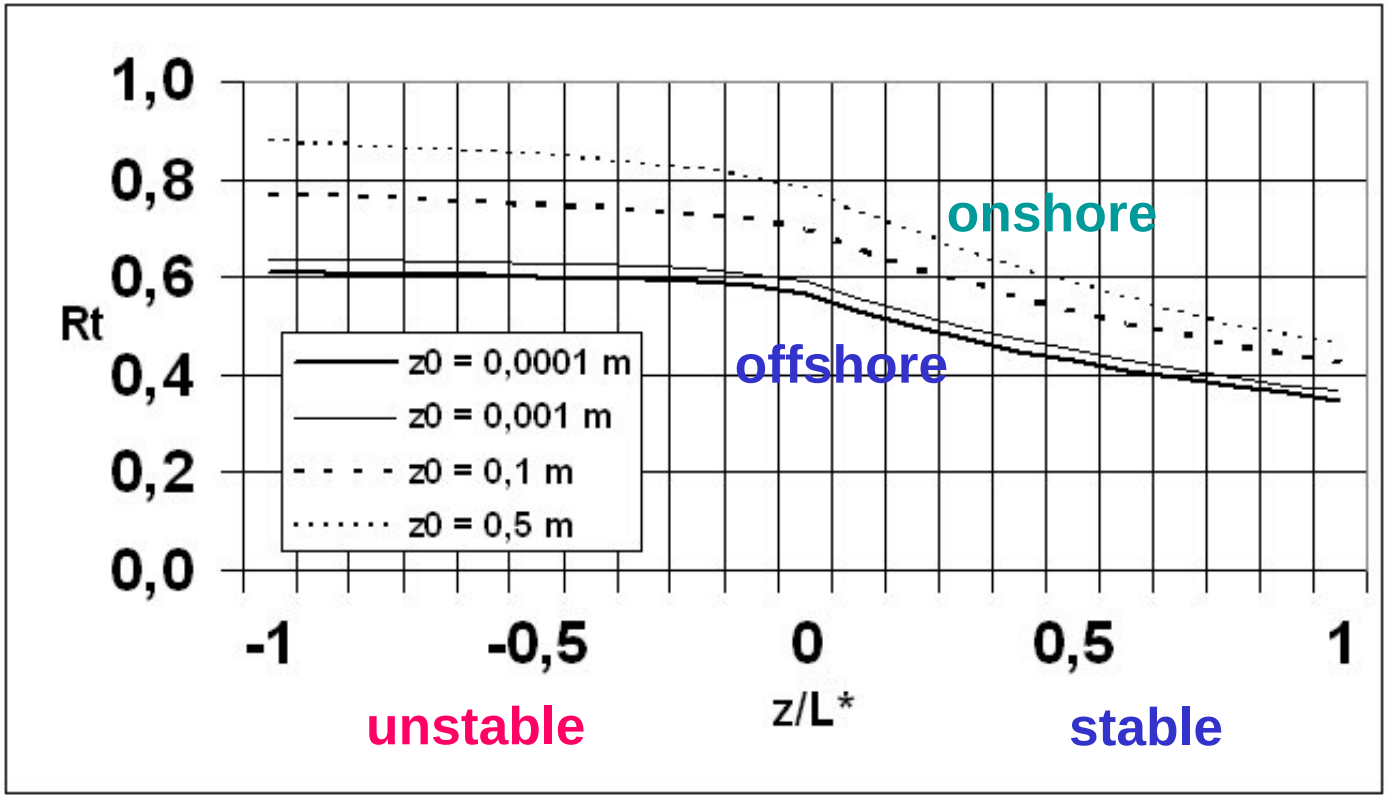


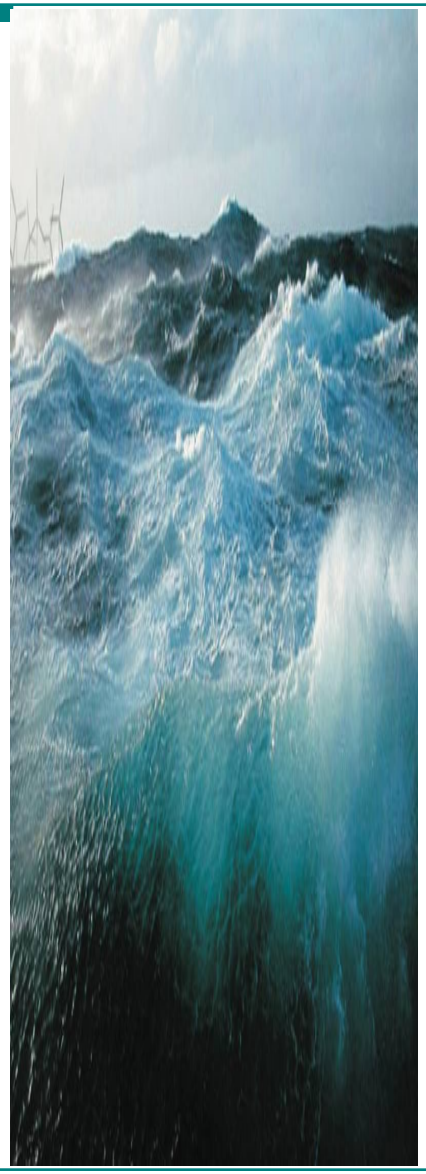

Fig. 1. Basic momentum budget for an ensemble of wind turbines in a turbulent flow. The momentum loss due to the turbines is compensated by downward turbulent momentum flux.

**Emeis, S., Frandsen, S., 1993:** Reduction of Horizontal Wind Speed in a Boundary Layer with Obstacles. Bound.-Lay. Meteorol., 64, 297-305.

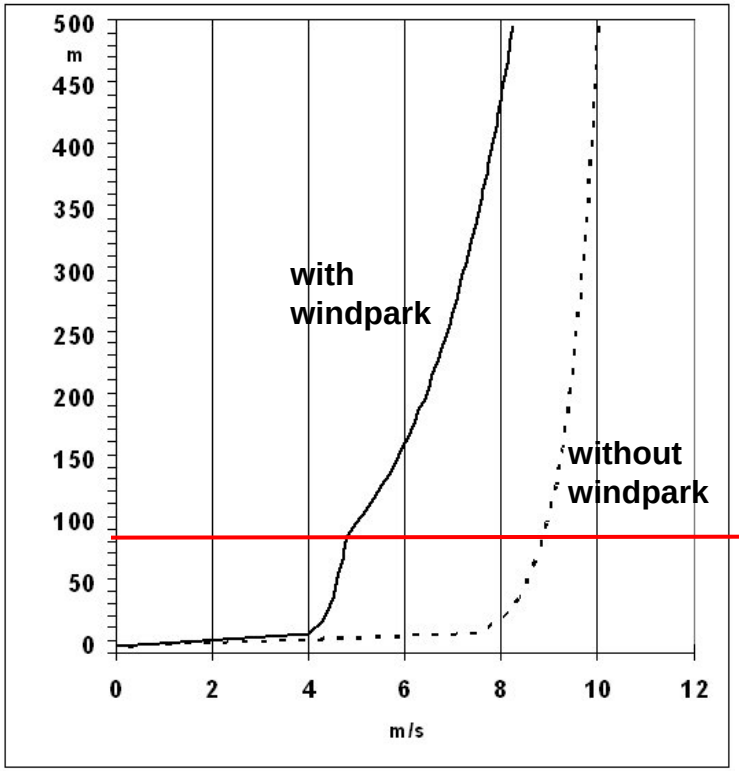
# momentum balance of a windpark in a turbulent flow : reduction of wind speed in hub height (enhanced EF93-Model)

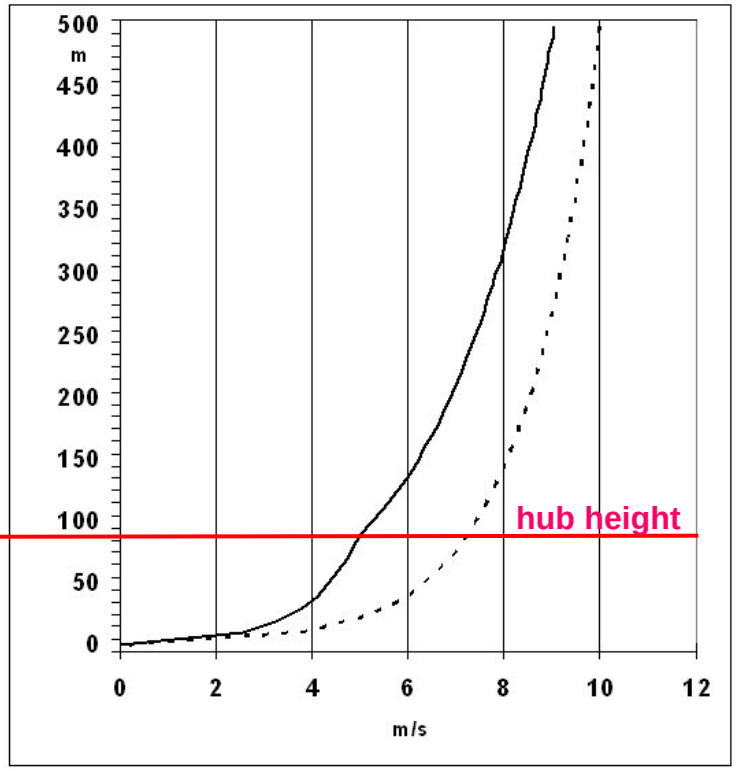



**the rougher the surface ➔ the more effective the windpark**



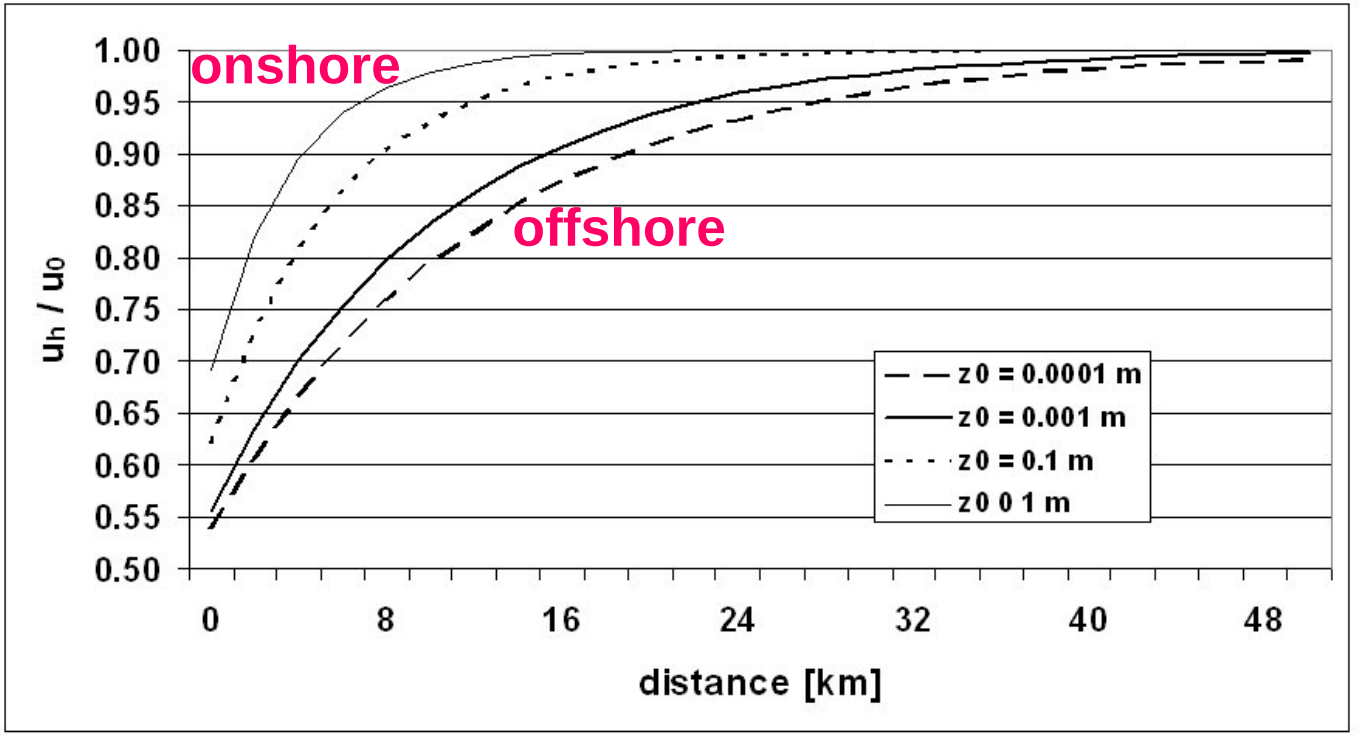
# momentum balance of a windpark in a turbulent flow : vertical wind profile neutral stratification (enhanced EF93-model)




**smooth ($z_0$ = 0.0001 m)** **u= 10 m/s** **rough ($z_0$= 1 m)**

# momentum balance of a windpark in a turbulent flow : length of wake of a wind park (enhanced EF93-model)




**neutral stratification, $u_0$ = 10 m/s**

# Summary and outlook

## difference offshore - onshore

**different surface (smoother, moving)**

**WEC operate mainly in Ekman layer not in Prandtl layer (except for very high wind speeds)**

**different boundary layer structure („young“ waves only in 30% of cases)**

**assumptions of IEC 61400 not always conservative**

**less turbulence leads to a lesser effectivity of windparks (➔ larger distance between WECs necessary)**

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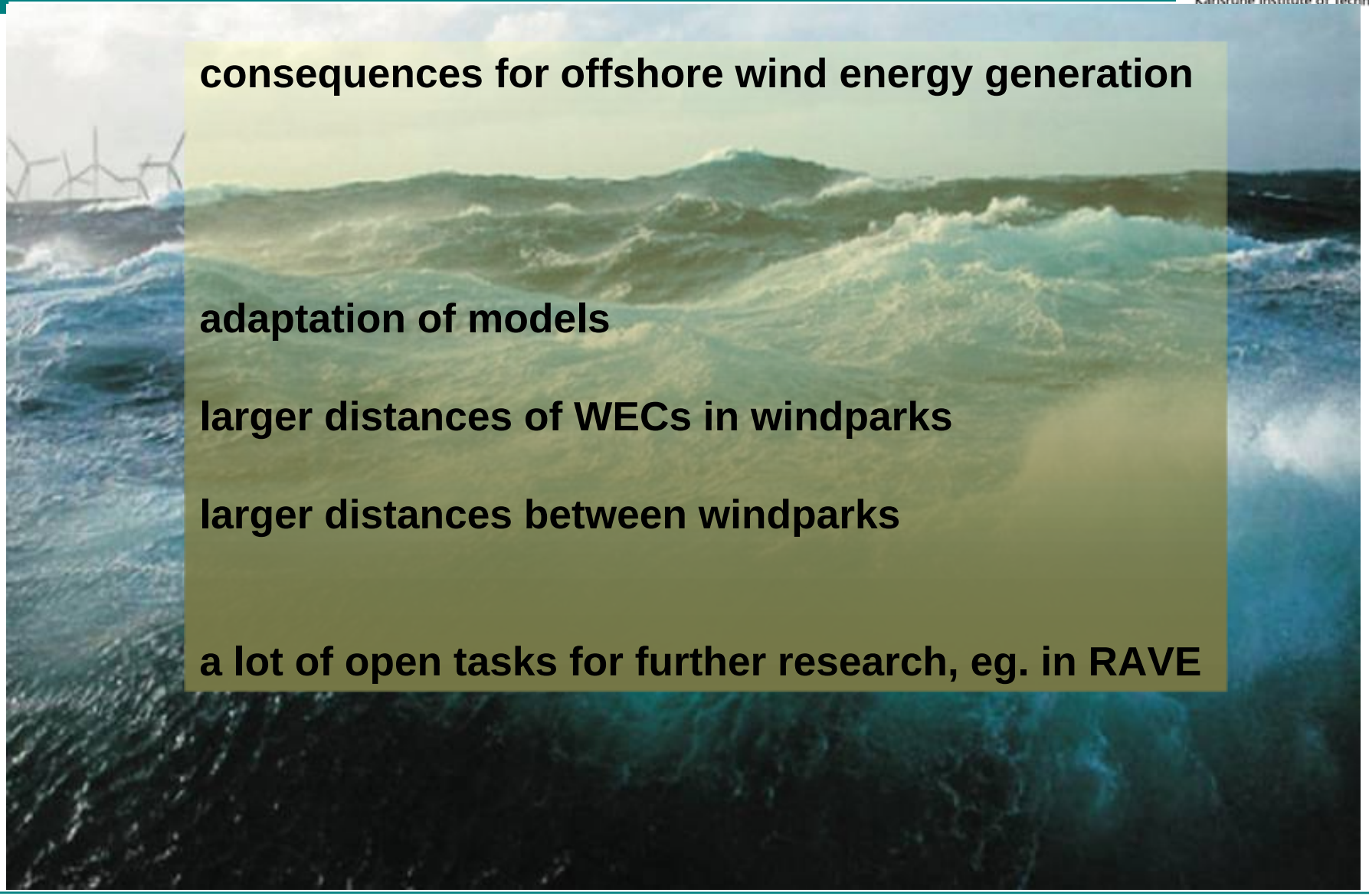


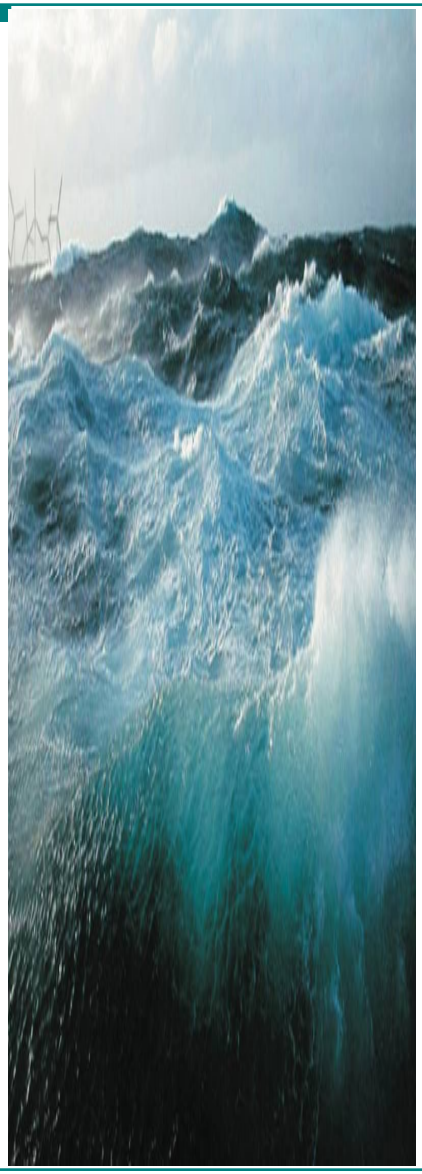
## consequences for offshore wind energy generation

**adaptation of models**

**larger distances of WECs in windparks**

**larger distances between windparks**

**a lot of open tasks for further research, eg. in RAVE**



## Thank you for your attention

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# End



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# Wellenhöhe als Funktion der Windgeschwindigkeit

**bisher an FINO1 beobachtet**

**Schätzung 50-Jahreswert**

| Sektor / Windgeschwindigkeit | 25 m/s | 30 m/s | 35 m/s | 40 m/s | Erklärte Varianz [$R^2$] in % |
|---|---|---|---|---|---|
| **nördlich (290 - 40°)** | 6,7 | 9,2 | 12,1 | **15,5** | 69,5 |
| **östlich (40 – 120°), instabil** | 5,2 | 7,0 | 9,2 | 11,8 | 75,2 |
| **südlich (120 – 210°), instabil** | 4,2 | 6,0 | 8,1 | 10,6 | 61,3 |
| **südlich (120 – 210°), stabil** | 3,4 | 4,8 | 6,5 | 8,5 | 53,0 |
| **westlich** | 4,1 | 5,3 | 6,6 | 8,1 | 56,6 |
| **östlich (40 – 120°), stabil** | 1,6 | 1,6 | 1,7 | 1,6 | 29,9 |



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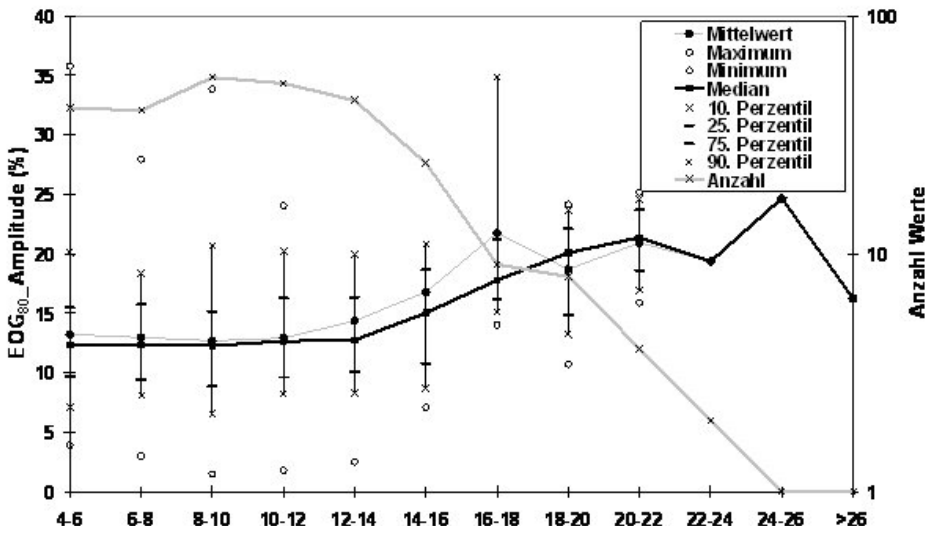
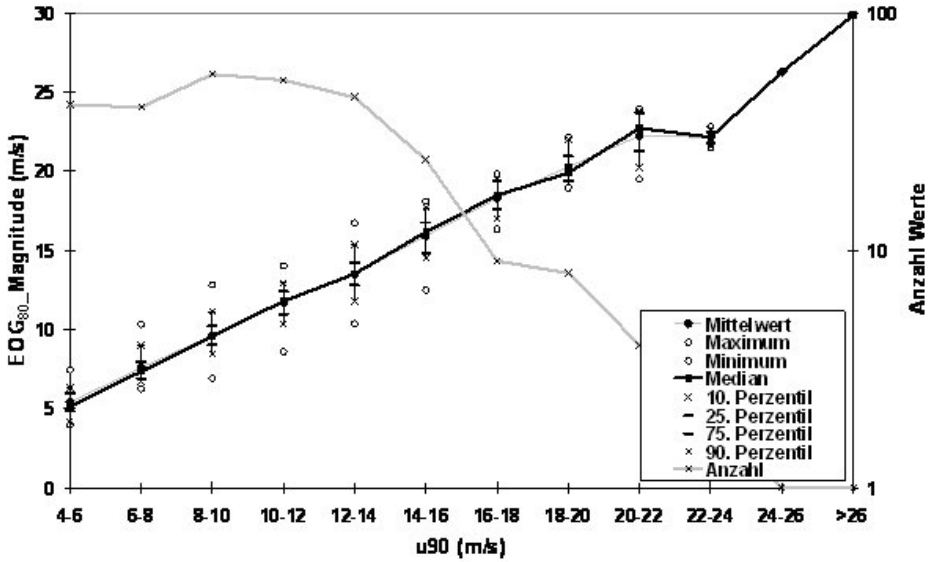
# Extreme operating gust (EOG)

**Amplitude (Diff. Min-Max)**




**Magnitude (Max)**



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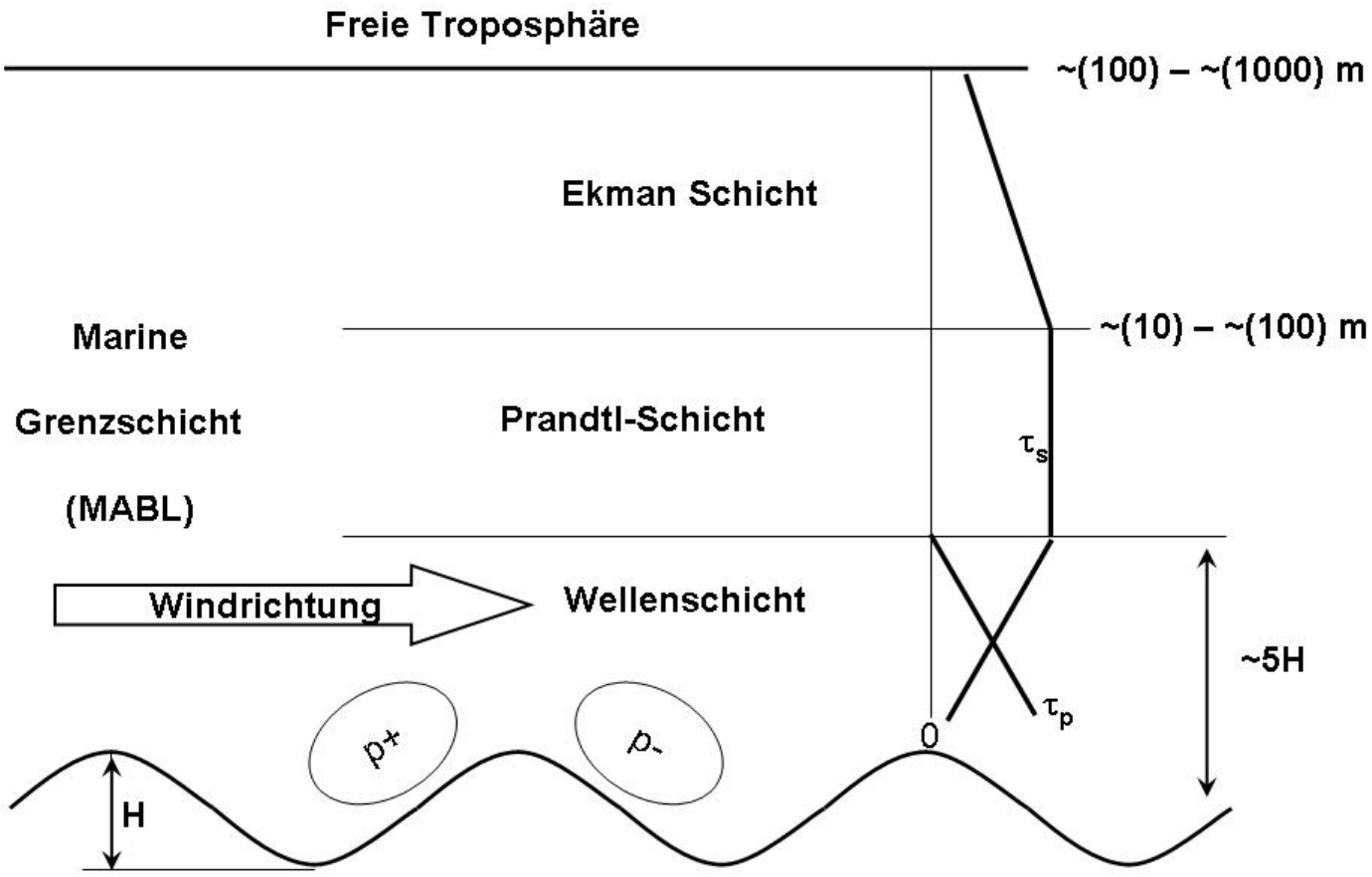
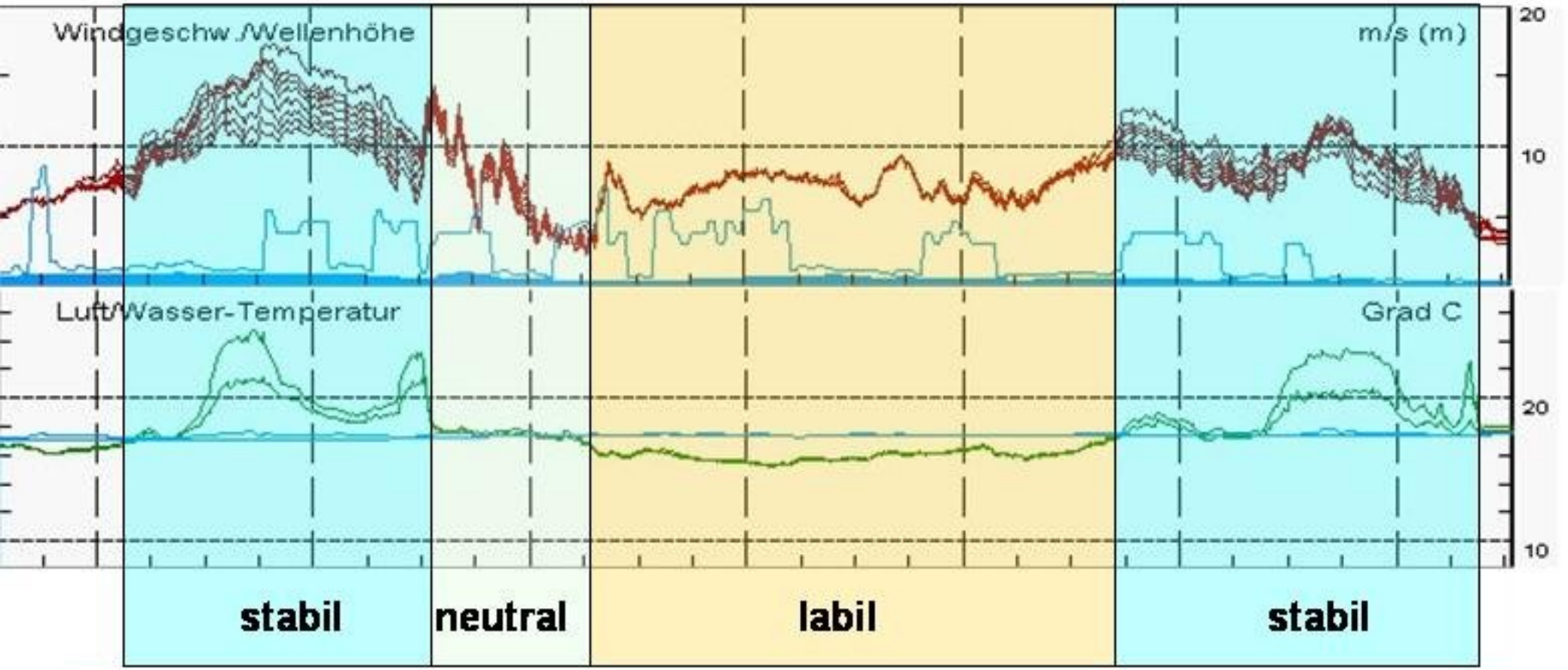
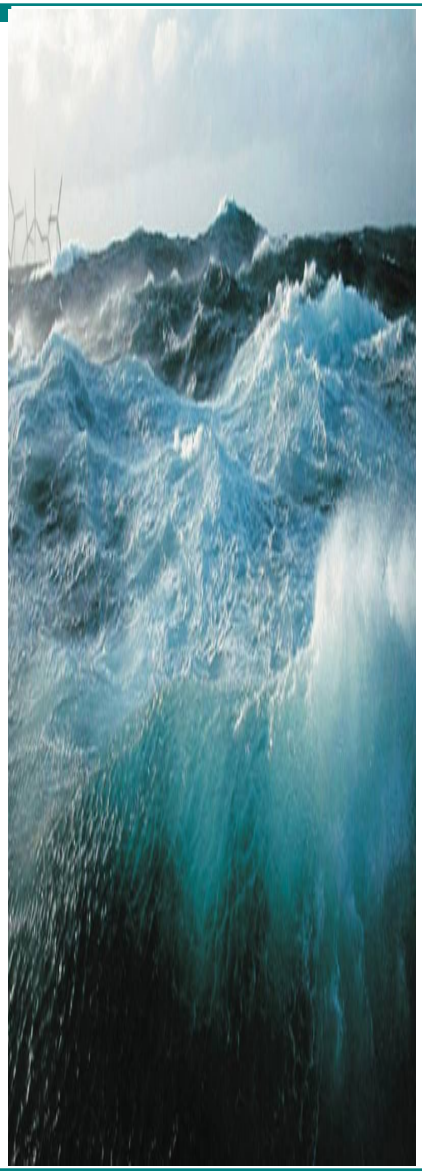
# Vertikalaufbau der marinen Grenzschicht

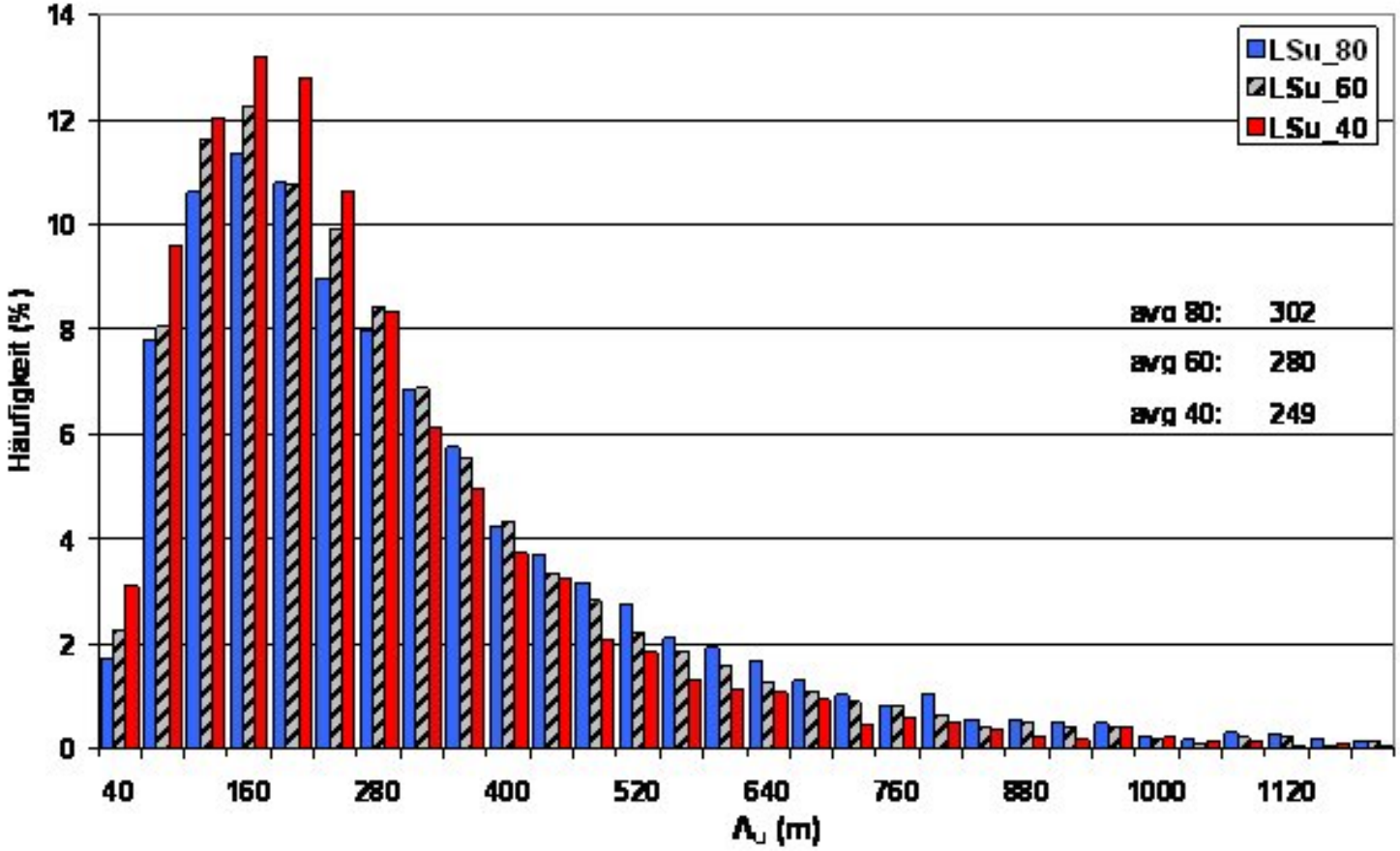


# Zeitreihen von der FINO1-Plattform: Windgeschwindigkeit und Luft/Wasser-Temperatur Woche bis zum 6. September 2005 11:46 Uhr





# Längenskalen der Turbulenzelemente



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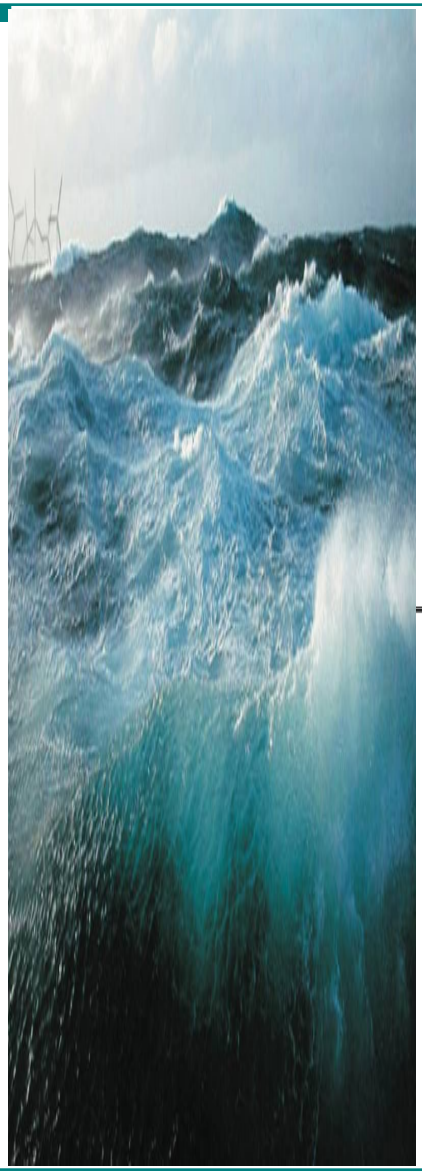
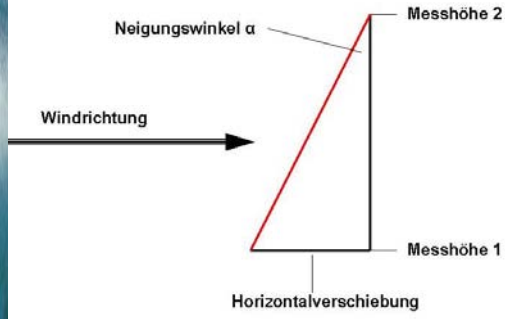
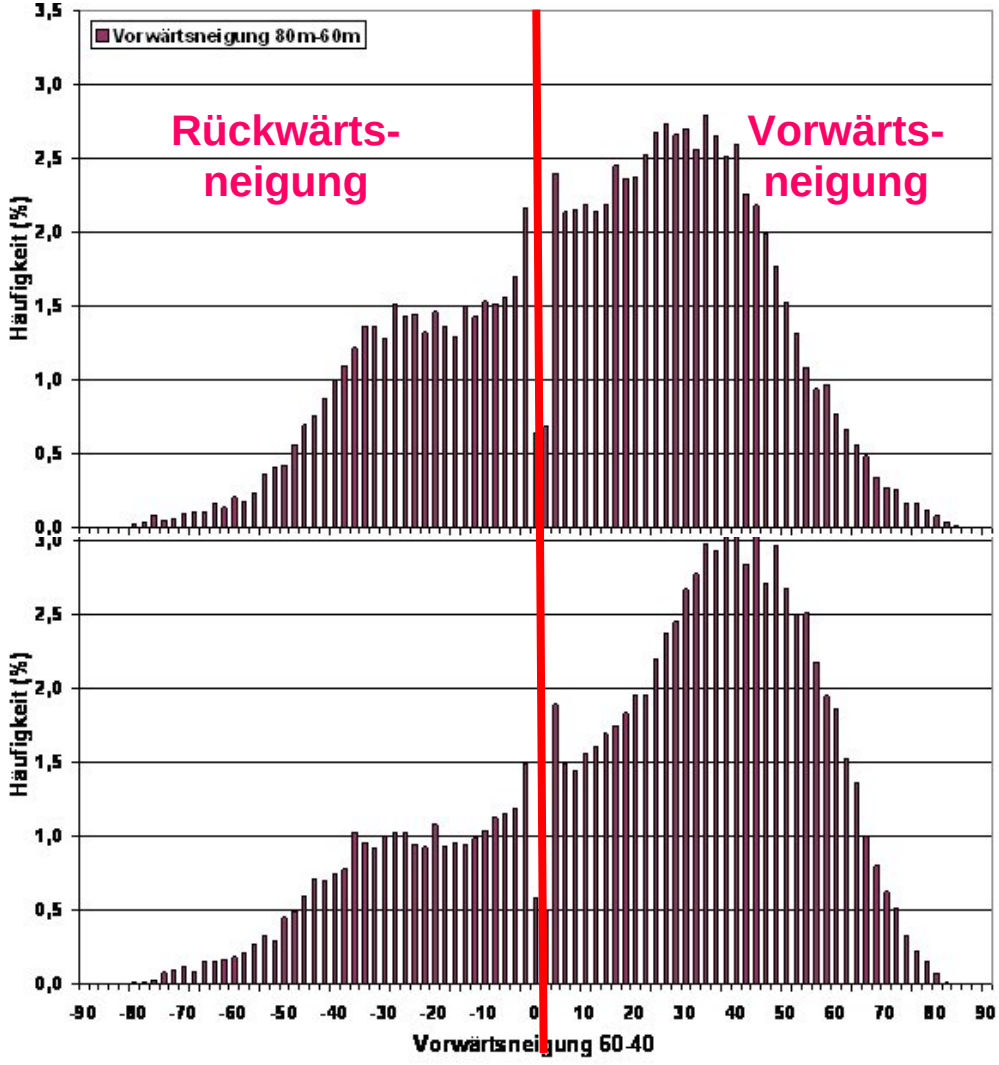


# Vorwärtsneigung der Turbulenzelemente

**60 bis 80 m**




**40 bis 60 m**



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# Extreme operating gust (EOG)

**Häufigkeit in Abhängigkeit von der Länge (relativ zur Häufigkeit für 10,5 s Länge)**

| 8 s | 10,5 s | 14 s |
|---|---|---|
| 1,60 | 1,00 | 0,63 |

**kürzere EOGs sind häufiger als die 10,5 s-EOGs der Norm**



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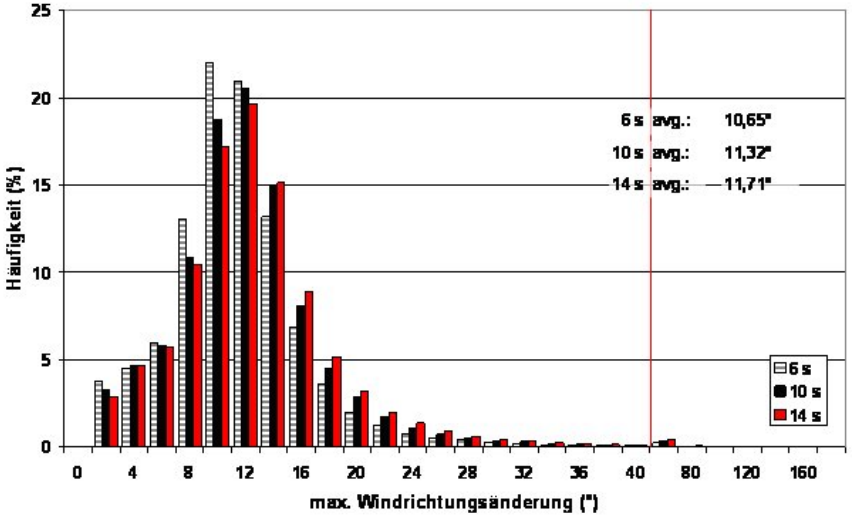
# Extreme direction change (EDC)

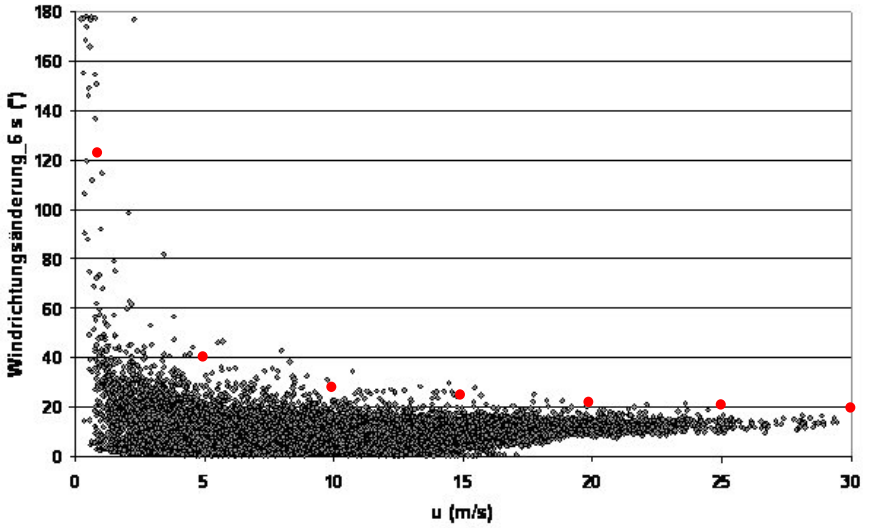
**Häufigkeits-verteilung für 6, 10 und 14 s**




**als Funktion der Windgeschw.**

**Vergleich mit 61400-1, Gl. 20:**

**D = 120 m**
**$\Lambda$ = 42 m**



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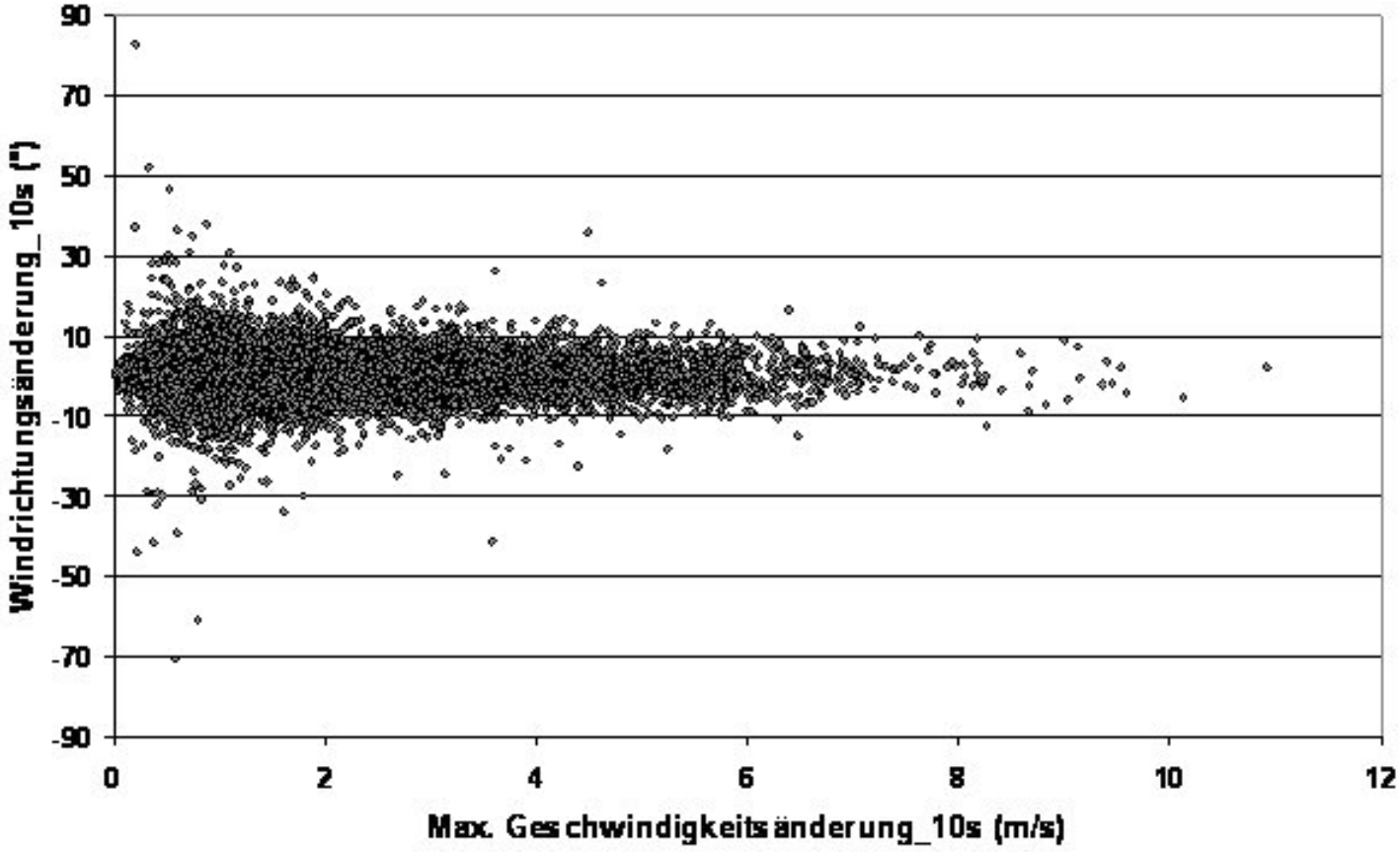
# Extreme coherent gust with direction change (ECD)



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# Extreme wind speed model (EWM)

**Der Hellmann-Exponent für die Extremwinde:**

für das 10 min-Mittel scheint 0,11 richtig

für die 3 s-Böe scheint 0,11 etwas zu hoch

**Der 50-Jahreswert für die Turbulenzintensität:**

0,11 erscheint ausreichend konservativ

(die Extrapolation der Daten ergibt ca. 0,10)



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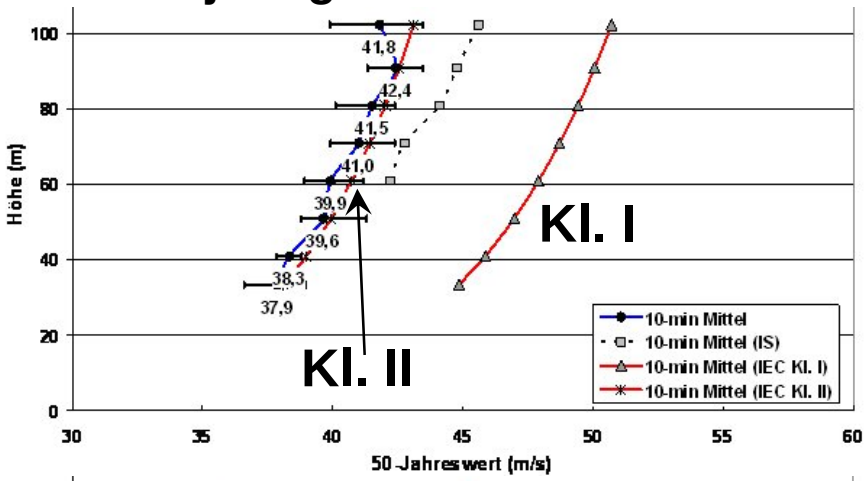
# Extreme wind speed model (EWM)

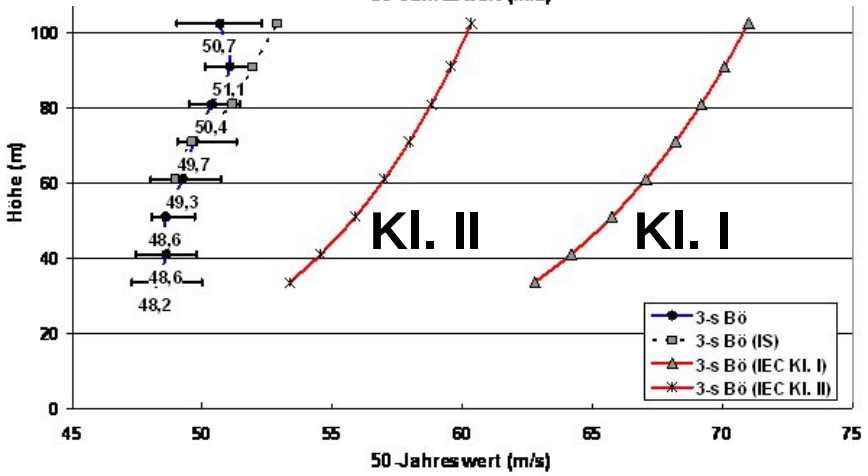
## Vertikale Profile der 50jährigen Extreme

**10 min-Mittel**




**3 s-Böe**

(mit 0,983 aus den 1 s-Daten errechnet)



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